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FINAL REPORT TO U.S. DEPARTMENT OF ENERGY

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Spin Physics Center
University of Michigan

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The Spin Physics Center's DoE-supported research from November 1, 2001 until April 30, 2003, when DoE effectively terminated its most recent 3-year Grant, is described in pages 1-14 of Part A.

The Spin Physics Center's research, during 1 November 1993 until October 31, 2003, which was supported by earlier parts of this Grant is described in pages 1-55 of Part B. Part B also describes its research during about July 1964 until October 31, 1993, which was supported by an AEC/ERDA/DoE Contract.

DISCLAIMER

10 July 2003

PROGRESS REPORT TO U.S. DEPARTMENT OF ENERGY
Spin Physics Center
University of Michigan

Overview

With the 1 November 2001 award of its 3-year Grant by the U.S. Department of Energy High Energy Physics Division, the Spin Physics Center has continued its research and development during 2002-2003:

- **SPIN@U-70 at IHEP-Protvino:** In February 2001, we were approved by IHEP to measure A_n in very-large-$P_\perp^2$ elastic *p-p* scattering at 70 GeV using our Solid PPT at the IHEP U-70 Accelerator in Protvino. All heavy parts of the 35 m-long Spectrometer were successfully installed in the Channel 8 extracted beam area of U-70, and two successful test runs occurred in November 2001 and April 2002. However, our 4-ton shipment of detectors and electronics was impounded by Russian Customs in March 2002 and was returned in November 2002. With the SPIN@U-70 Agreement suspended until US-Russia relations and conditions for collaboration improve, our IHEP colleagues conducted a third test run in April 2003.
- **SPIN@J-PARC:** In December 2002, we submitted an LoI, SPIN@J-PARC, to use our now-returned detectors and electronics and our never-impounded Solid PPT for a similar experiment at the new 50 GeV very-high-intensity proton accelerator at J-PARC in Japan; the first beam is expected in 2007. We presented the LoI to the J-PARC NPF Committee on 27 June 2003.
- **Solid PPT:** We are continuing R&D to improve the reliability of our state-of-the-art Michigan Solid Polarized Proton Target (PPT), which was to be shipped to IHEP for the Nov-Dec 2002 SPIN@U-70 Run. If the SPIN@U-70 suspension continues, we may use the Solid PPT in SPIN@J-PARC.
- **Ultra-Cold Jet:** Recent R&D on our unique Ultra-cold Spin-polarized Atomic-hydrogen Jet Target allowed stable operation for 18 hours with an average intensity of 10^{15} H s^{-1} and an unexpectedly small beam size of less than 4 mm HWHM, resulting in a world record density of 10^{12} spin-polarized hydrogen atoms cm^{-3}. High density is especially important for experiments needing precise vertex identification such as CNI and high-$P_\perp^2$ elastic spin experiments. We hope to reach a density 10^{13} cm^{-3} by late 2004.
- **CE-83 at IUCF:** We studied for the first time the spin-flipping behavior of both the vector and tensor polarizations of a stored 270 MeV deuteron beam. We measured a vector polarization spin-flip efficiency of 94 ± 1% and found an interesting tensor polarization spin-flipping behavior. These results may allow a new generation of polarized deuteron scattering experiments and were submitted to PRL in May 2003.
- **SPIN@COSY:** In December 2002 our SPIN@COSY experiment at the 3 GeV COSY polarized storage ring in Jülich, Germany was approved for two runs. In February 2003, we had a successful first run by spin-flipping COSY's first stored polarized deuteron beam; using an air-core rf-dipole built by COSY with our advice, we reached about 50% spin-flip efficiency. In April 2003, using the same rf-dipole, we spin-flipped a stored polarized proton beam with an efficiency of 99.3 ± 0.1%; we obtained this high precision by measuring the polarization after 30 spin-flips. In May 2003, we were approved for 4 more week-long runs in 2003-2004. We plan to strengthen the rf-dipole by using both ferrite and water-cooling and then extend the IUCF and COSY results for both polarized protons and polarized deuterons.
- **MIT-Bates Storage Ring:** Using a prototype air-core rf-dipole and a Siberian snake in the MIT-Bates Storage Ring, we spin-flipped a 670 MeV polarized electron beam, with an efficiency of 94.5 ± 2.5%. Then we constructed a much stronger rf-dipole using surplus ferrite from the ZGS RF cavity. Using this ferrite rf-dipole in a November 2002 run, we achieved an electron spin-flip efficiency of about 98.8 ± 0.3% by measuring the polarization after 11 spin-flips.
- **SPIN@RHIC:** We tried to help improve the RHIC beam polarization by hosting the 6-9 November 2002 *Workshop on Increasing the AGS Polarization.* A new short-term plan to overcome the AGS depolarizing resonances was developed at the Workshop; this is now being implemented for RHIC's FY2004 Run.

A. SPIN@U-70 Experiment

The SPIN@U-70 Experiment is a fundamental study of very-large-$P_\perp^2$ spin effects in *p-p* elastic scattering at IHEP-Protvino. In December 1996, we submitted the SPIN@U-70 proposal [28] to IHEP to study A_n in very-large-$P_\perp^2$ *p-p* elastic scattering at 70 GeV using the Michigan solid NH_3 Polarized Proton Target (PPT) target at U-70. Using: the 2 10^{34} luminosity with U-70's extracted proton beam; the Michigan's PPT's 90% polarization; and the NEPTUN-A spectrometer's large solid angle, we can precisely measure A_n at $P_\perp^2$ up to 12 $(GeV/c)^2$. This would considerably exceed the world's record of 7 $(GeV/c)^2$ from our 1990 AGS experiment.

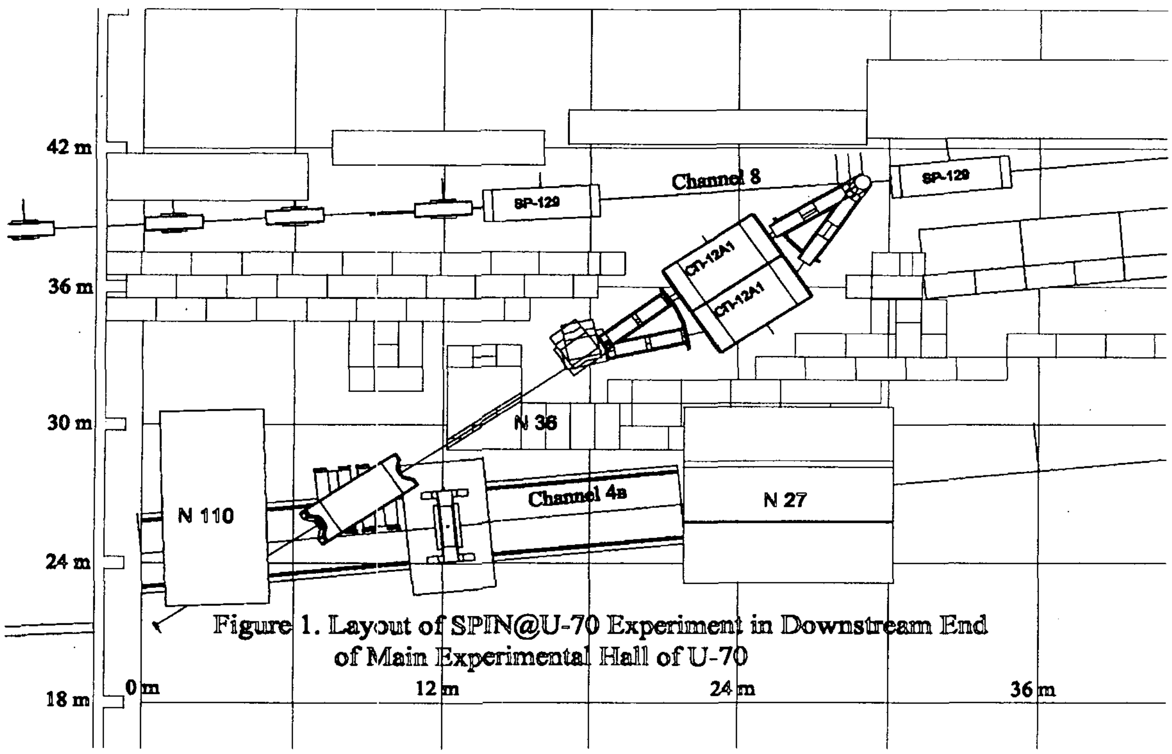

Figure. 1 Diagram of SPIN@U-70 Experiment [14, 17, 28] in downstream end of U-70 Main Experimental Hall.

SPIN@U-70 Collaboration **20 November 2000**

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- On 11 March 2002, Michigan's 3567 kg $231,000 shipment of detectors and electronics for SPIN@U-70 arrived at Moscow's SVO Airport. This shipment was impounded by Russian Customs and contained the equipment needed for the April 2002 unpolarized Test Run, but fortunately not the $600,000 Solid PPT.
- After long and complex negotiations, led by Michigan's President and Provost, the impounded shipment was returned to Michigan on 4 November 2002, with no significant damage; the University then paid IHEP $25,000 of University funds for the shipment's return.

Although the shipment of equipment was impounded, the 19-26 April 2002 SPIN@U-70 Test Run was somewhat successful, due to the extraordinary efforts of our IHEP collaborators; they assembled some primitive but working all-Russian detectors and electronics in only a few weeks with some help from the few Michigan physicists then at IHEP. The resulting data, [14, 17] shown in Fig. 2, indicates that the 35-m-long Elastic Recoil Spectrometer is effective at discriminating against inelastic and other background events.

There was a third Test Run of the SPIN@U-70 Spectrometer in late-April 2003, using an unpolarized CH_2 target supplied by Michigan. Partly due to the strained US-Russian relations due to the Iraq War, we declined IHEP's invitation to join this Run. Our IHEP Colleagues obtained rather clean 5-fold coincidences between 3 detectors from the 35-meter-long Recoil-proton Spectrometer and two detectors from the small forward hodoscope all placed in a line downstream of the target at about 6° from the Channel 8 extracted beamline shown in Fig 1. Some data from this Run is shown in Fig. 3. We hope that relations between DoE and MINATOM soon improve so that we can continue this important and fundamental experiment, which involved great effort and expense by both sides.

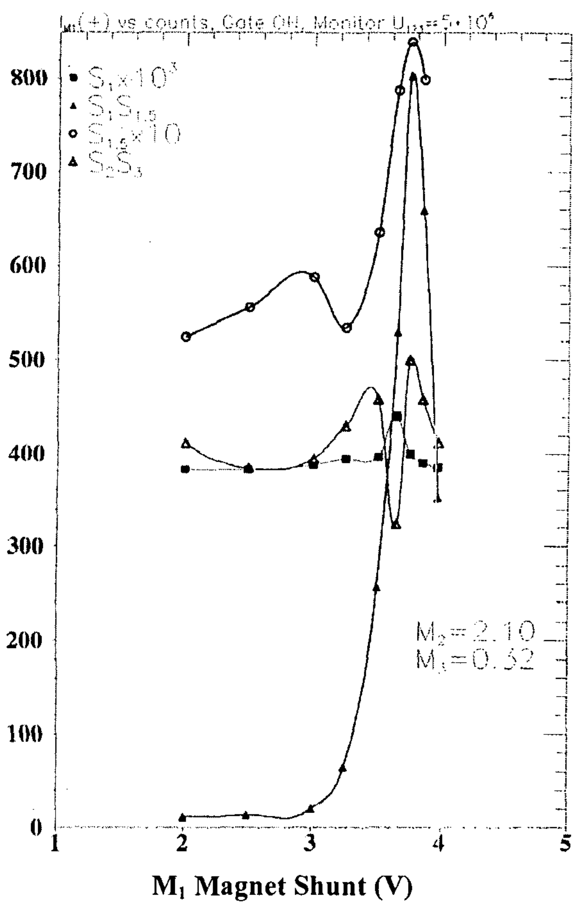


Figure 2. Magnet Curve: The Elastic Recoil Spectrometer event rate, $S_1 \cdot S_{1.5}$, is plotted against the Current in the 3-m-long 68-ton M_1 dipole bending magnet. The signal to background ratio is about 80 to 1 in the elastic peak. [14, 17]

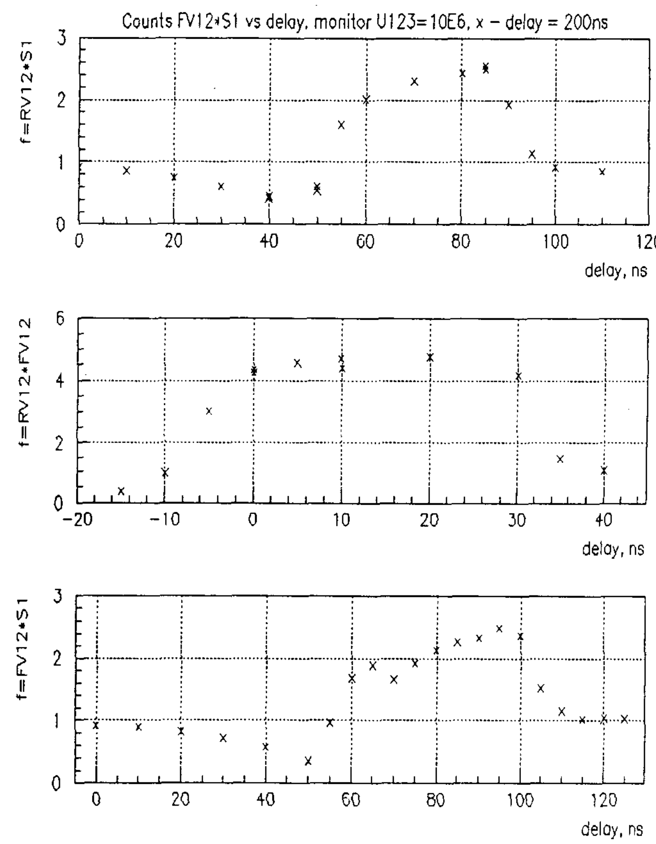


Figure 3. Plot of coincidences between detectors from the 35-meter-long Recoil-proton Spectrometer and the small forward hodoscope placed in a line aimed towards the target at about 6° from the Channel 8 extracted beamline.

B. SPIN@J-PARC (High-$P_\perp^2$ *p-p* Elastic A_n at the J-PARC 50 GeV Accelerator)

If SPIN@U-70 cannot be completed, we may try to use our recently improved Michigan Solid PPT as a target at the new 50-GeV Proton Synchrotron in Japan (J-PARC); its first beam is scheduled early in 2007. This new facility should have a 50 GeV extracted proton beam of about 3 10^{14} protons per pulse every 3 seconds, and a primary beam area which might hold our 35-meter-long Elastic Recoil Spectrometer. Two of us attended the NP02 Meeting (27-29 September 2002 at Kyoto, Japan) to explore bringing the Solid PPT to Japan to measure A_n at high-$P_\perp^2$. [17] The response has been positive; we submitted the **attached** LoI [25] in December 2002 and then presented it at the 26-28 June 2003 Meeting of the J-PARC NPF Committee at KEK.

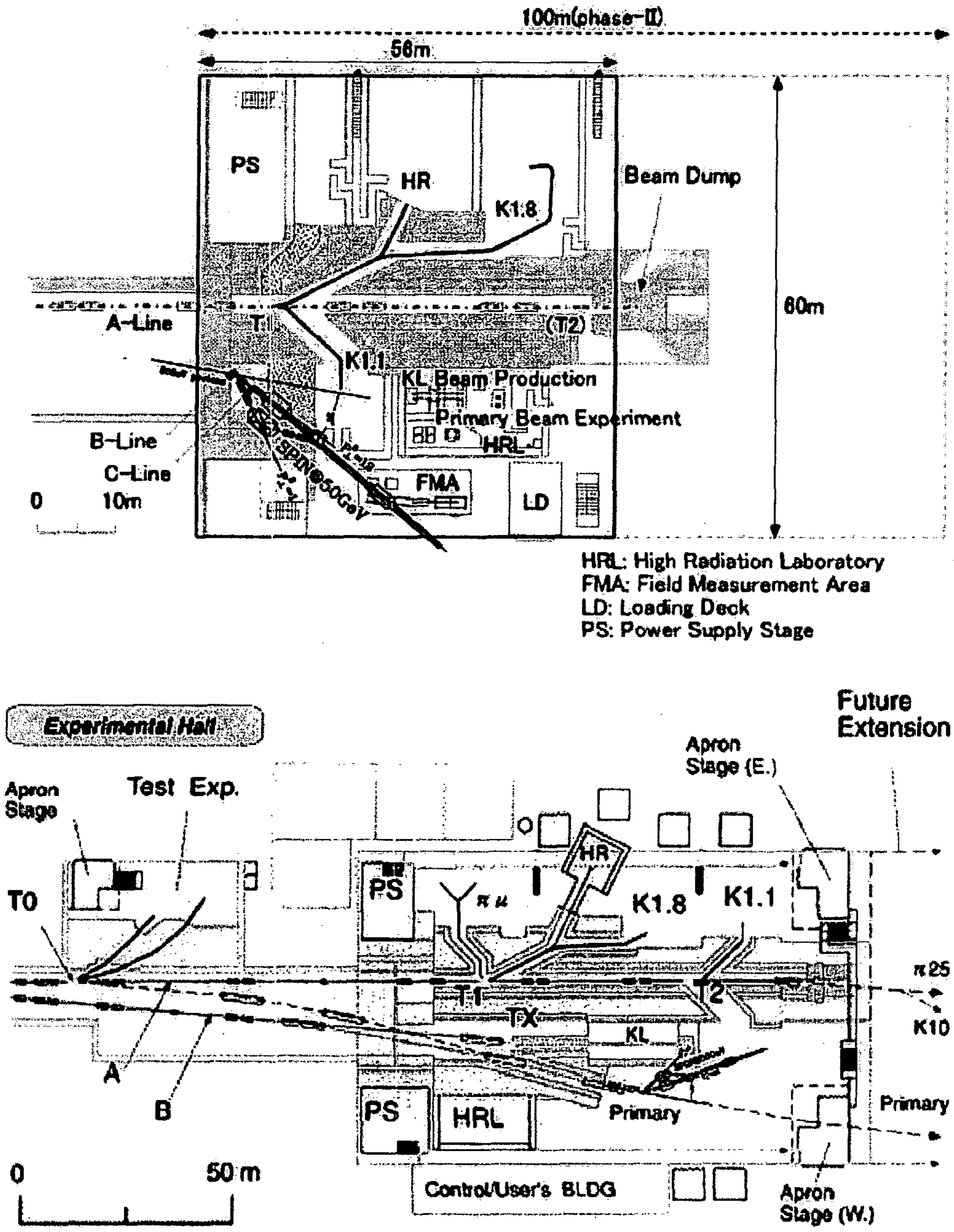


Figure 4. Possible placement of the 35-meter-long Elastic Recoil Spectrometer in the J-PARC 50 GeV primary beam line. (Upper Fig. is in Phase I area; Lower Fig. is in Phase II area.) [25]

C. Michigan Solid Polarized Proton Target

The Center is continuing to test and improve the state-of-the-art 5 T at 1 K Michigan Solid Ammonia (NH_3) Polarized Proton Target (PPT) [15, 20] and to prepare it for possible shipment to Protvino or Japan. [25, 28] Since our first SPIN@U-70 shipment was impounded by Russian Customs, we will not ship the PPT to Russia until the conditions for collaboration improve and we receive assurances from MINATOM that future shipments will not be impounded. Because of the impoundment, we may use the PPT for a similar experiment at the high intensity 50-GeV J-PARC Proton Synchrotron in Japan, which is scheduled for first beam in 2007. [25]

Recent improvements in the Michigan Solid-PPT have focused on increasing its reliability and include:

- New uni-polar power supply for the 5 T highly uniform superconducting magnet;
- New coil configuration for the NMR system;
- New wiring, Kel-F material holder, and RuO temperature sensor for the ^{4}He evaporation refrigerator;
- New Varian power supply for the 140 GHz microwave system.

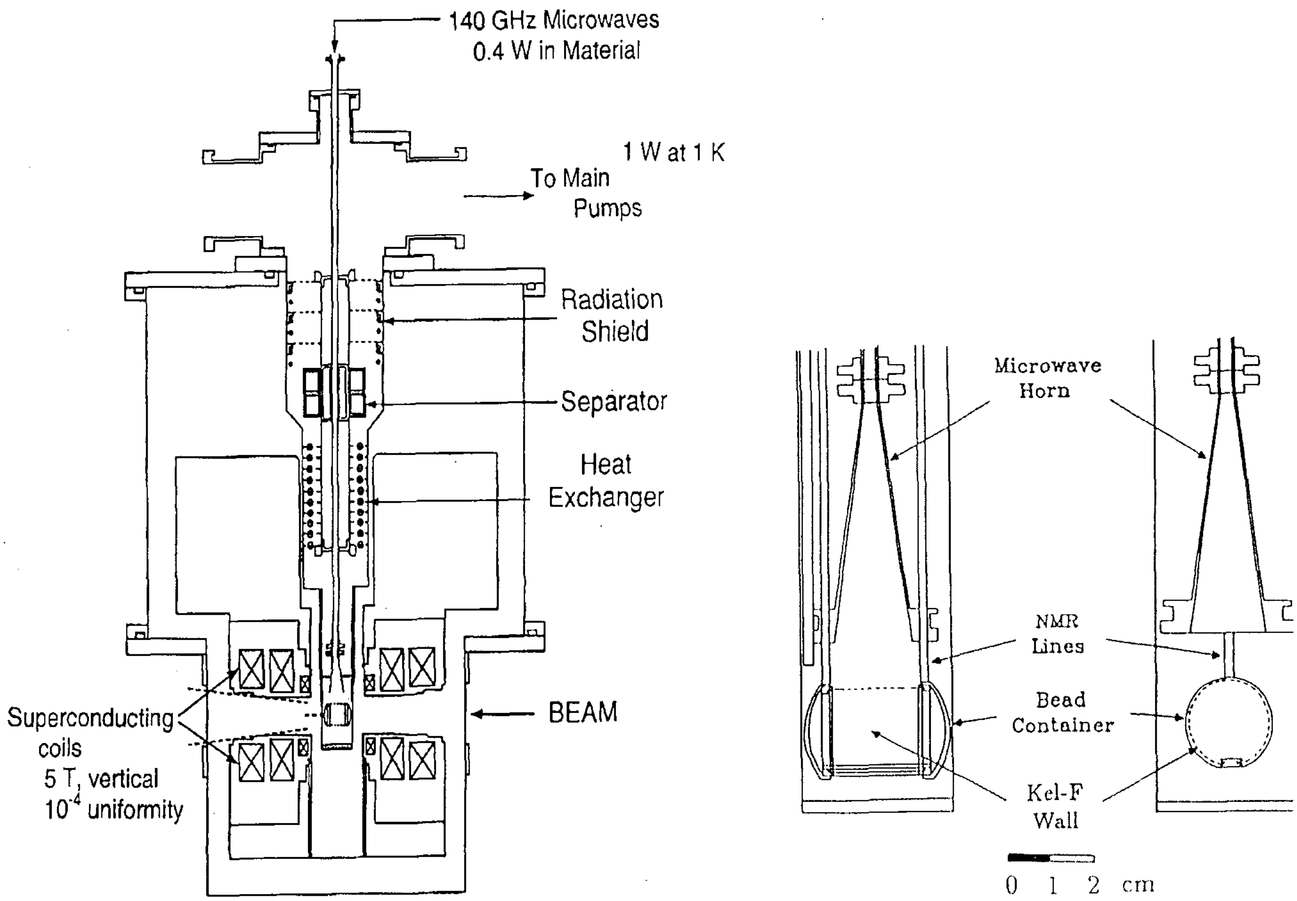


Figure 5. The state-of-the-art Michigan Solid Polarized Proton Target: the superconducting magnet produces a highly uniform 5 T field; the He^4 cryostat produces 0.9 W of cooling power at 1 K; the 140 GHz microwaves are focused into the small target cavity filled with irradiated ammonia (NH_3); the proton polarization in frozen NH_3 at 5 T and 1 K is over 90%. An expanded view of the NH_3 cavity is shown on the right. [15, 20]

D. Michigan Ultra-Cold Spin-Polarized Proton Jet

The present commissioning arrangement of the 12 T at 0.2 K Ultra-cold Spin-polarized Atomic-hydrogen Jet is shown in Figure 6. Our aim is to improve the Jet with the following goals:

- Reach our original goal thickness of 10^{13} atoms cm^{-2};
- Exceed our current world density record of 1 10^{12} atoms·cm^{-3} due to the Jet's unexpectedly good beam optics; [16, 19, 21]
- Install and commission the cryogenic rf transition unit [21] to increase the Jet's proton polarization from its present 50% to near 100%.

Last year, the beam intensity seemed limited by the beam scattering from the high vacuum pressure due to the evaporation of the separation cell's superfluid He^4 film. Thus, we increased the Jet's cryo-pumping capacity to decrease this problem. However, we recently discovered that a much thicker superfluid He^4 film could cover the build-up of frozen H atoms and thus, significantly lower the He^4 evaporation due to the H atoms' large heat of recombination in the separation cell. This change reduces the vacuum pressure and allows us to run for much longer periods with a stable and high beam intensity. [16] We now plan to continue to develop this Jet target, by further improving: the superfluid He^4 film; the prototype cryogenic RF cavity; and the Maser polarimeter.

Due to the Jet's Ultra-cold 0.17 K temperature, the energy spread of the spin-polarized hydrogen atoms in its beam is only ± 2%. This has resulted in unprecedented beam optics for a neutral atomic beam; thus, the measured beam size in the Compression Tube detector is less than 4 mm HWHM as shown in Fig. 7. The unexpectedly small beam size gives a world record density of $1 \cdot 10^{12}$ spin-polarized hydrogen atoms cm^{-3}. This high density is especially important for experiments needing precise vertex identification such as a CNI elastic polarimeter. Recent tests studied the Jet's properties and stability at different operating conditions and found stable operation at an average intensity of about $1 \cdot 10^{15}$ H s^{-1} for at least 18 hours, as shown in Fig. 8.

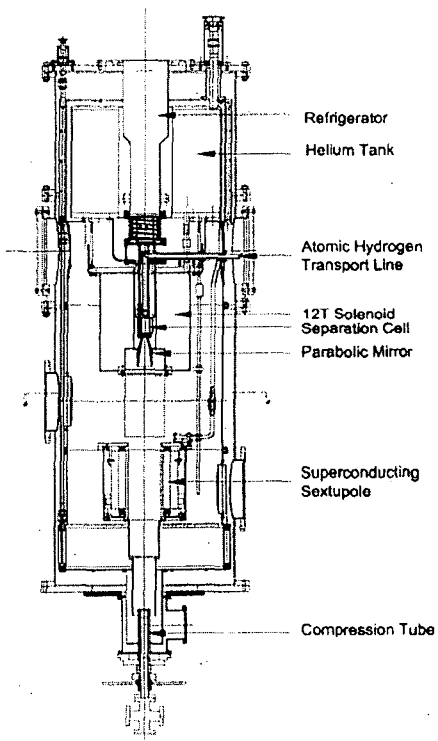


Figure 6. Michigan Ultra-Cold Spin-Polarized Proton Jet during testing. The Compression Tube detector measures the beam with 1.4 mm precision. [16, 19, 21]

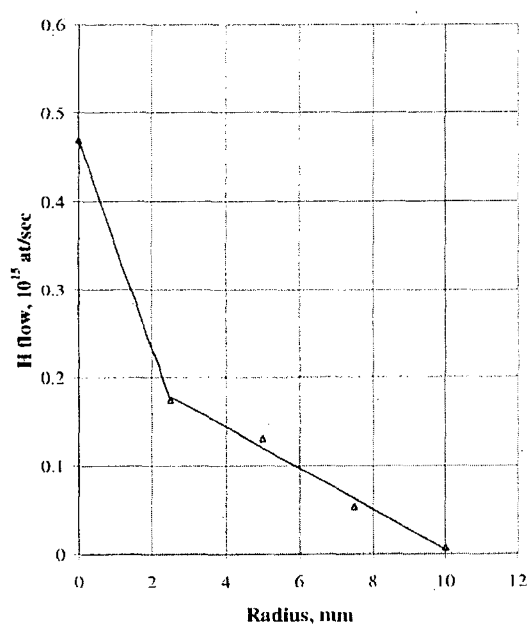
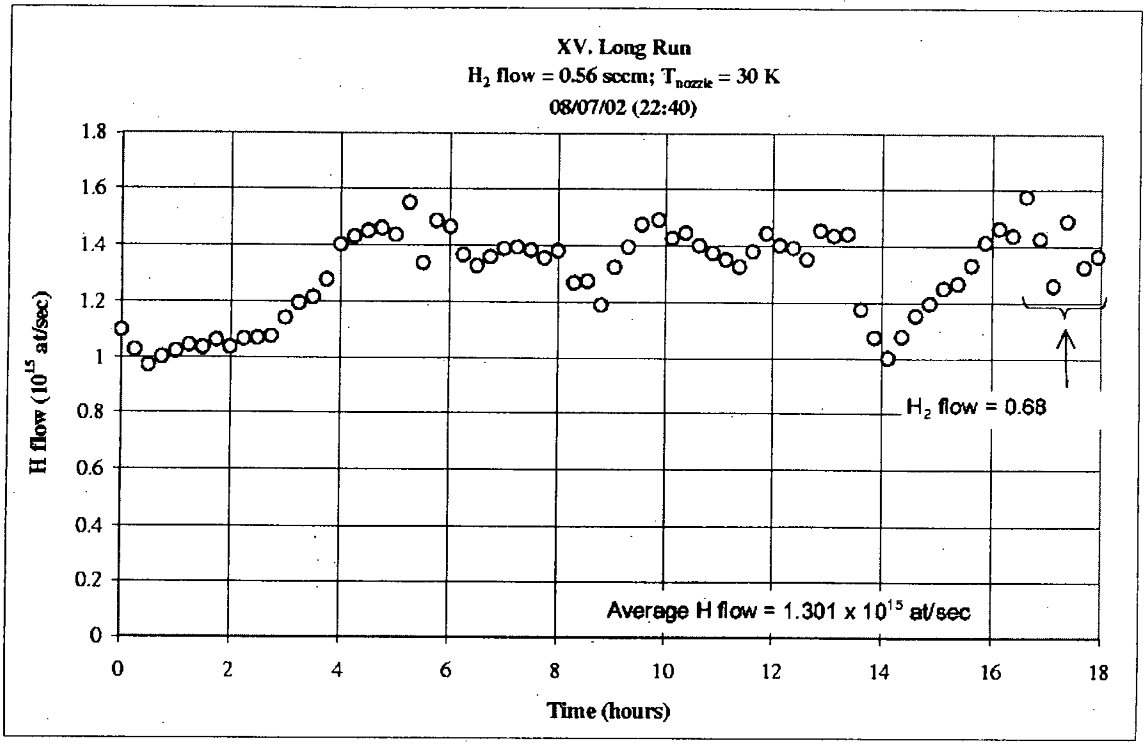


Figure 7. The Michigan Jet's measured radial beam intensity. [19]



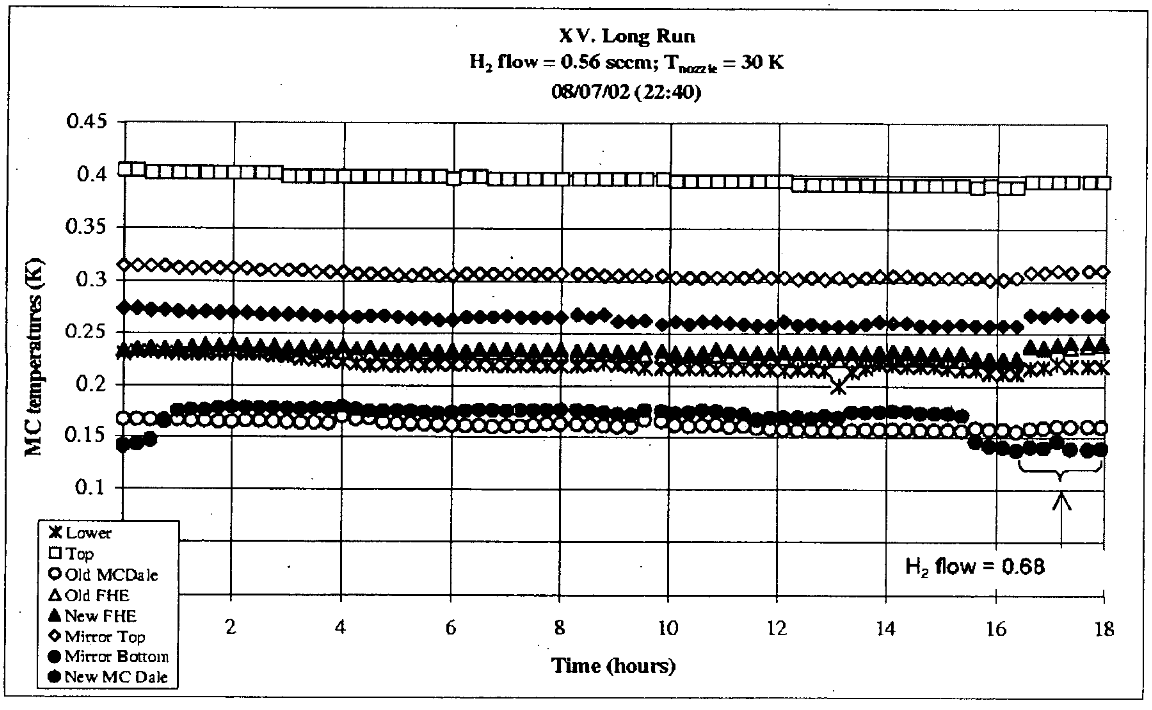


Figure 8. Data from the 18-hour-long August 2002 Run, which ended only when the Helium supply was depleted. The detector's slot had an area of 15.4 mm^2. The H^0 beam's velocity was 280 m/s and its proton polarization was about 50%; its high average density of 4 10^{11} H^0 cm^{-3}, high average thickness of 8 10^{11} H^0 cm^{-2}, and excellent stability for more than 18 hours were apparently due to the much thicker superfluid He^4 film for this Run and a similar June 2002 Run. The upper figure shows the polarized proton flux and the lower figure shows the temperatures of various parts of the Jet. [21]

E. Spin Manipulation of Polarized Proton and Deuteron Beams at IUCF

In May 2000, the Indiana University Cyclotron Facility (IUCF) approved our final Proposal, [29] which focused on the Accelerator Spin Physics research allowed by the 1999 upgrade of the IUCF Cooler Ring, using the Cooler Injector Synchrotron (CIS) and its CIPIOS Polarized Ion Source, shown in Fig. 9. We increased the maximum spin-flipping efficiency of polarized protons, stored in a ring with a Siberian snake, to 99.93 ±0.03% [2,12,18, 24] by using an upgraded rf-dipole. We also made detailed studies of higher-order snake resonances and the surprising behavior of an *exactly* 100% Siberian snake; these data are not yet fully analyzed or published. [7, 8]

We also made the first experimental study of the spin manipulation of polarized deuterons. A new generation of polarized deuteron scattering experiments is emerging as an interesting new area of subatomic physics. As an important first step towards these polarized deuteron scattering experiments, we studied the acceleration, storage, and spin-flipping of spin-1 polarized deuterons in the IUCF Cooler Ring. Our previous spin studies focused on beams of spin-½ particles: protons at IUCF and electrons at MIT-Bates.

In CE-83 at IUCF, we studied for the first time a polarized beam of deuterons, which are spin-1 particles with both vector and tensor polarization. We studied both spin-flipping and the polarization lifetimes of 270 MeV vertically polarized deuterons stored in the Cooler Ring. After optimizing the rf solenoid's parameters during July 2002, we spin-flipped the vector polarization of stored polarized deuterons with a spin-flip efficiency of 94 ± 1% (Fig. 11). We also investigated the behavior of both vector and tensor deuteron polarizations for complete and partial crossings of rf-induced depolarizing resonances (Fig.10). We also studied the vector and tensor polarizations' lifetimes near the resonance; the lifetimes' ratio was 1.9 ± 0.2. We recently submitted these results in two papers. [3, 4]

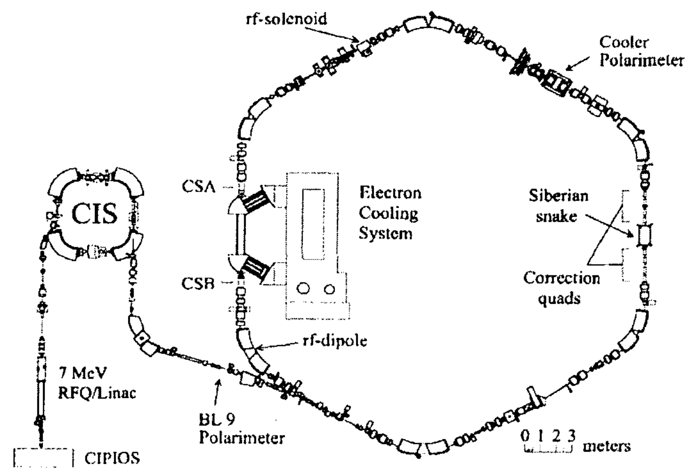


Figure 9. IUCF Cooler Ring with the Cooler Injector Synchrotron (CIS) and its CIPIOS Polarized Ion Source. [2-4, 7-8, 12-13, 24]

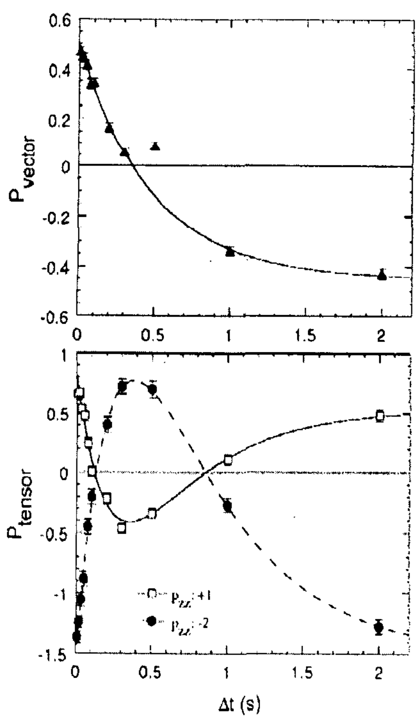


Figure 10. The measured vector and two tensor deuteron polarizations at 270 MeV are plotted vs the rf solenoid ramp time Δt. The solenoid's frequency range Δf was ±2 kHz, and its rms ∫B*dl* was 0.7 T·mm. The curve in the top is a fit using Eq. (7). The solid and dashed lines in the bottom part are fits to a new "tensor" Froisart-Stora Equation. [13, 18]

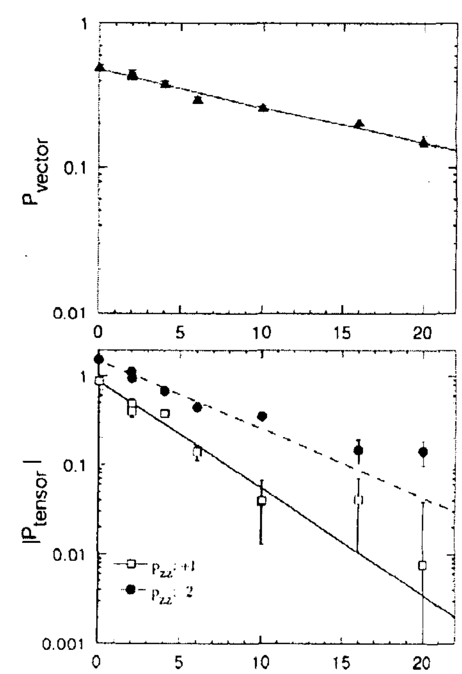


Figure 11. The measured vector and 2 tensor deuteron polarizations at 270 MeV are plotted against the number of frequency sweeps. The rf solenoid's frequency ramp time Δt was 1.5 s; its frequency range Δf was ±0.75 kHz, and its rms ∫B*dl* was 0.7 T·mm. The lines are fits using $P_n = P_i \cdot \eta^n$. [13, 18]

F. SPIN@COSY: Spin Manipulation Experiments at COSY in Jülich, Germany

With the Summer 2002 closing of the IUCF Cooler Ring, we plan to continue our highly successful Siberian snake and spin manipulation experiments at the COSY 3 GeV polarized proton Storage Ring in Jülich, Germany, which has outstanding hardware and is shown in Fig. 12. After one of us attended the September 2002 Workshop on COSY Physics, [18] we formed the new SPIN@COSY Collaboration with colleagues at COSY, Bonn, Hamburg, J-PARC and Brookhaven to continue at COSY our investigations of:

- The spin manipulation of polarized deuterons and of polarized protons;
- Higher-order snake depolarizing resonances for polarized protons;
- The very interesting behavior of an *exactly* 100% Siberian snake.

The **attached** SPIN@COSY Proposal [27] was presented to the COSY PAC on 2 December 2002; it was approved with high priority for Runs in February and April 2003. The first SPIN@COSY run occurred during 3-10 February 2003; it coincided with the first storage of polarized deuterons in COSY. Despite the rapid timescale, our Collaboration successfully spin-flipped 1.85 GeV/c polarized deuterons, with a spin-flip efficiency of almost 50%, as shown in Figure 13. [22]

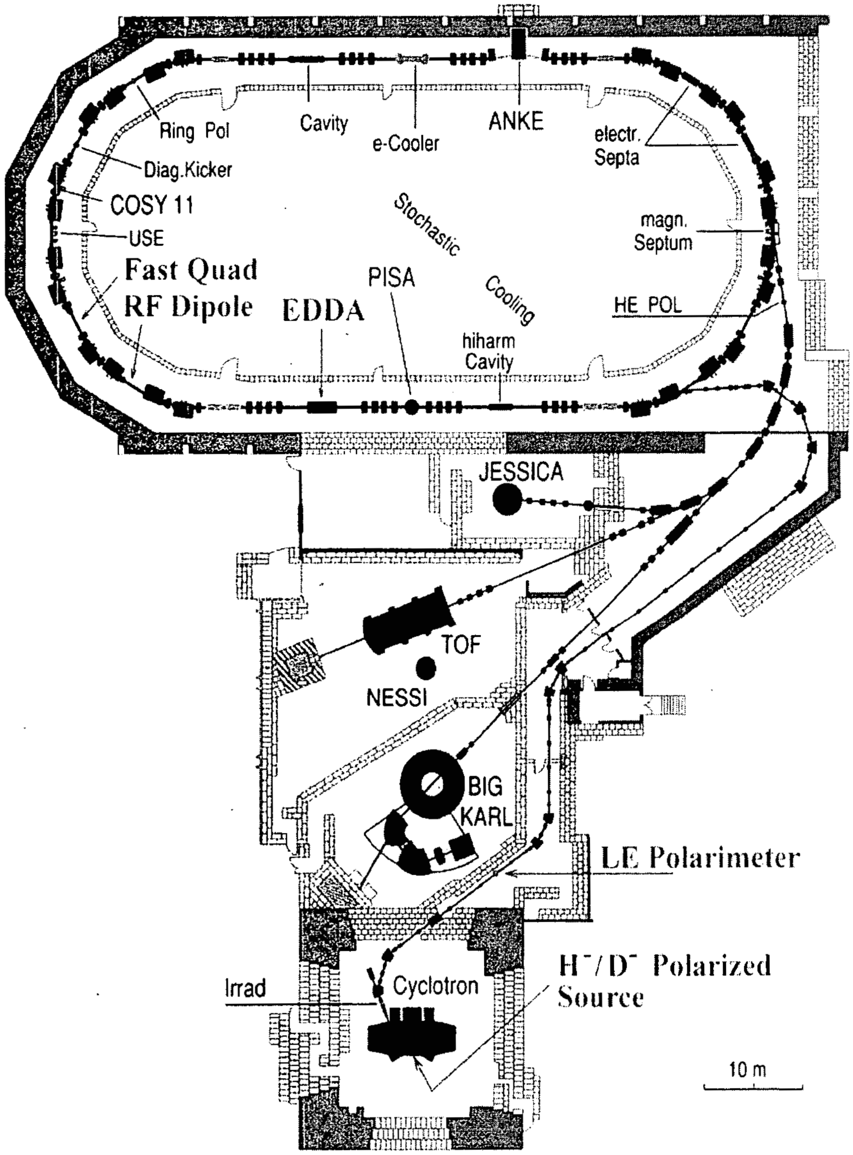


Figure 12. Layout of COSY showing its Storage Ring, injector Cyclotron and polarized ion source. The EDDA and Low Energy (LE) polarimeters are also shown. [5, 22, 26, 27]

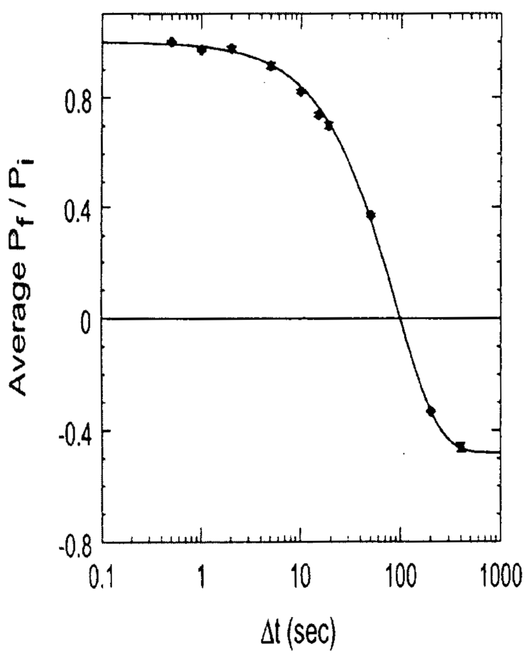


Figure 13. Spin-flipping the vector polarization of 1.85 GeV/c deuterons at COSY. The ratio of measured polarizations is plotted vs. the rf dipole's ramp time. [22]

The first SPIN@COSY run with polarized protons occurred during 22-28 April 2003; we studied the spin-flip efficiency with a beam of 1.94 GeV/c polarized protons stored in the COSY ring. By adiabatically ramping an rf dipole's frequency through an rf-induced spin resonance, we were able to spin-flip the polarization of a stored proton beam. After first determining the resonance's frequency, we optimized the dipole's spin-flipping parameters by measuring the spin-flip efficiency, while varying: the frequency ramp's $\int Bdl$; its ramp time (Δt) in Fig. 14; and its frequency range (Δf) in Fig. 15; we did these studies, first for one spin-flip, and then for 11 spin-flips to increase the precision 11-fold.

We then set the rf-dipole's frequency ramp time Δt at 10s, its frequency range Δf at ± 4 kHz, and its rms $\int Bdl$ at 0.11 T·mm. We then obtained a more precise determination of the spin-flip efficiency by measuring the polarization after 1, 11 and 30 spin flips as shown in Fig. 16. We fit the data to the equation $P_n = P_i \cdot \eta^n$, which gave a measured spin-flip efficiency of 99.3 ± 0.1 %. This result implies that an rf dipole should allow efficient spin-flipping even in high energy proton rings.

At its 28-29 April 2003 Meeting, COSY's PAC approved the **attached** SPIN@COSY-2 Proposal [26] for 4 more runs during the next two years with high priority. We now plan to enhance the rf dipole's strength by building a ferrite box around it and using water-cooled coils to allow running at a higher current and thus a higher $\int Bdl$. This should allow further spin-flip efficiency increases.

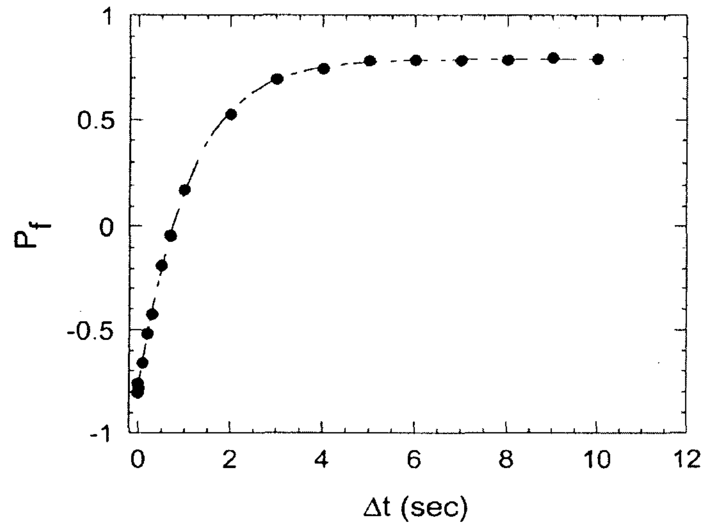


Figure 14. The proton polarization at 1.94 GeV/c is plotted against the rf-dipole ramp time Δt. The rf-dipole's frequency range Δf was ± 5 kHz, and its $\int Bdl$ was 0.11 T·mm rms. The curve is a fit using the Froissart-Stora Equation. [5]

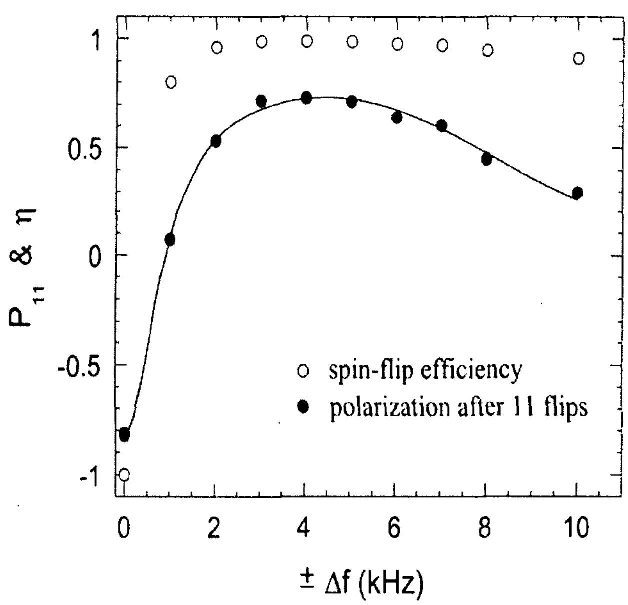


Figure 15. The 1.94 GeV/c proton polarization, after 11 spin-flips, is plotted against the rf-dipole's frequency range Δf. The open dots show the corresponding spin-flip efficiency. [5]

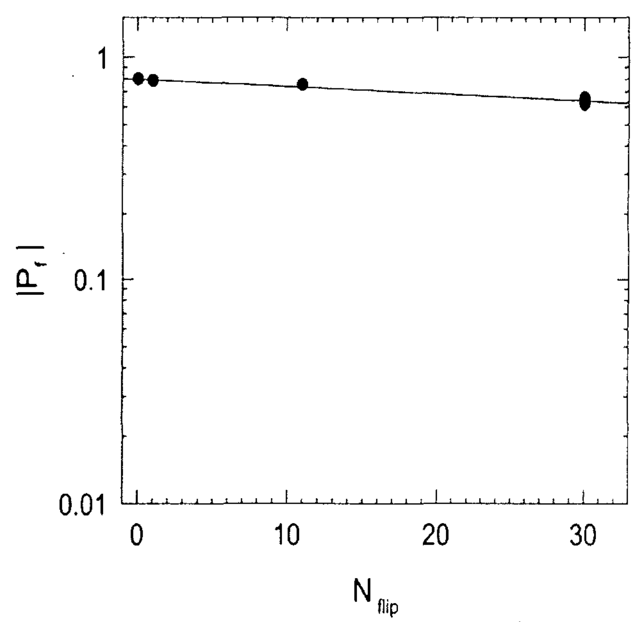


Figure 16. The measured proton polarization at 1.94 GeV/c is plotted vs. the number of spin-flips. The rf-dipole's frequency ramp time Δt was 10s, its frequency range Δf was ± 4 kHz, and its rms $\int Bdl$ was 0.11 T·mm. The line is a fit using $P_n = P_i \cdot \eta^n$ [5].

G. Spin Manipulation of Polarized Electron Beams at MIT-Bates Storage Ring

In February-March 2000, Michigan participated in studies at MIT-Bates Storage Ring, shown in Figure 17, which stored polarized electrons for the first time with their new Siberian snake containing two BINP superconducting solenoids. The snake's 5 normal and skew quadrupoles were tuned with our help to compensate for the x-y coupling and focusing due to the strong solenoids.

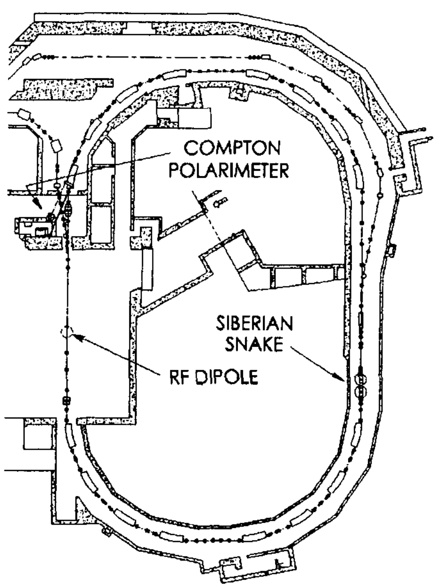


Figure 17. The MIT-Bates Storage Ring showing the prototype rf dipole, the Compton polarimeter, and the Siberian snake. [1, 6]

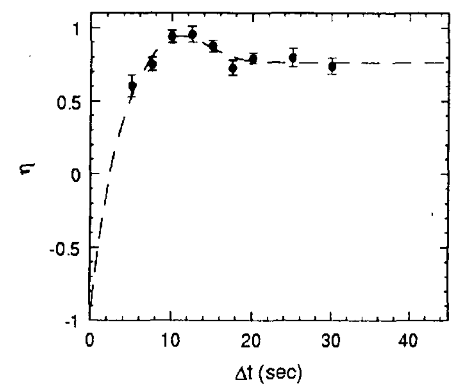


Figure 18. Spin-flipping efficiency η of the stored polarized electron beam plotted as a function of the ramp time Δt. [1]

In January 2001, together with MIT, we used a prototype air-core rf dipole magnet to spin-flip 670 MeV horizontally polarized electrons, stored with a nearly full Siberian snake, in the new MIT-Bates Storage Ring. We flipped their spins by ramping the rf dipole's frequency through an rf-induced depolarizing resonance. After optimizing the frequency ramp's parameters, we used multiple spin-flipping to measure a spin-flip efficiency of 94.5 ± 2.5%, as shown in Figure 18. [1] The spin-flip efficiency was apparently limited by the $\int Bdl$ of the air-core prototype rf dipole magnet. This unexpectedly high efficiency indicates that efficient spin flipping of the Ring's stored polarized electron beam should be possible by using a stronger ferrite spin flipper.

Based on these studies and our recent experience at IUCF, we designed, fabricated and tested at Michigan a 14-fold-stronger ferrite rf-dipole, using surplus ferrite from the ZGS rf cavity and a tuned LC circuit; this dipole is shown in Figure 19. It was then tested and shipped to MIT-Bates for a November 2002 study of spin-flipping polarized electrons in the Storage Ring. After optimizing the spin-flipping parameters, we used eleven spin flips to measure a spin-flip efficiency of about 98.8 ± 0.03%, as shown in Fig. 20; [6] the dipole's $\int Bdl$ was 0.34 T·mm and its Δf was ±2 kHz. [6] The curve is a fit assuming two depolarizing resonances: the strong rf resonance, which fully flips the spin for Δt above 0.2 s, and a much weaker resonance, which flips it a second time for Δt above 10 s.

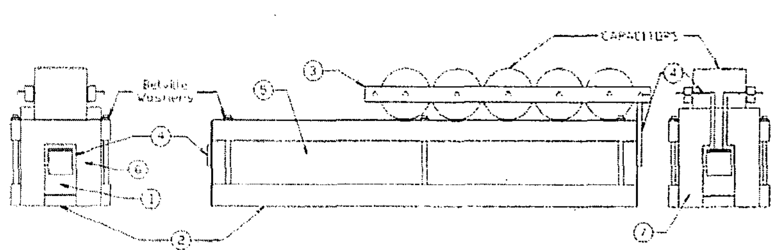


Figure 19. Ferrite RF Dipole for spin-flipping electrons in the MIT-Bates 1 GeV Storage Ring with the capacitors for its tuned LC circuit. [6] The circles and arrows indicate the:
1. Ferrite core; 2. Aluminum frame; 3. Copper rod;
4. Copper wire; 5, 6, & 7. G-10 shield.

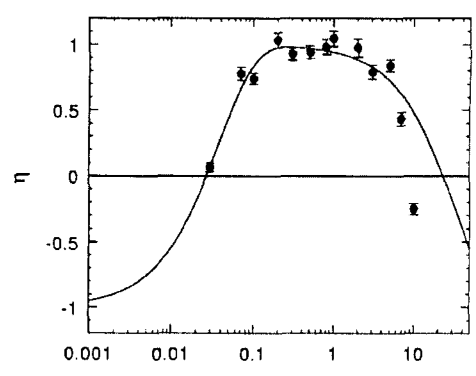


Figure 20. Measured spin-flip efficiency of 850 MeV polarized electrons plotted vs. the rf-dipole frequency sweep time. [6]

H. Workshop on *Increasing the AGS Polarization*

The reason for organizing the 6-9 November 2002 Ann Arbor Workshop on *Increasing the AGS Polarization* was the low AGS polarization injected into the new and unique RHIC multi-hundred-GeV polarized proton collider. The large and surprising spin asymmetries, discovered at lower energy accelerators, suggest that this polarized proton collider may be especially important. [30] The four Siberian snakes in the two RHIC rings can now maintain high polarization during acceleration to 100 GeV and storage. However, the 30-40% injected polarization from the AGS resulted in an average RHIC polarization of only about 30% during its FY2003 run. Clearly one needs to improve the AGS polarization

The Workshop's goal was to assemble a group of polarization experts to focus intensely for 4 days on how to increase the AGS polarization, and to document it precisely and quickly. The Workshop achieved this goal due to the dedication, hard work, and creativity of the 22 participants (8 from Brookhaven, 6 from Michigan, 2 from Cornell, and one from Argonne, COSY, DoE, JLab, KEK and Portland). The recently published Workshop Proceedings [23] should help Brookhaven's staff to implement the "short-term" Plan 1, developed at the Workshop, which is outlined in Thomas Roser's below Summary Table. This should make the FY2004 polarized RHIC run even more successful than the recent FY2003 run.

TABLE 1. Methods to overcome depolarizing spin resonances

	Imperfection resonances	Strong intrinsic resonances	Weak intrinsic resonances	Coupl. intr. resonances	Set-up information	Polarimeter	Meas. duration
COSY	corr. dipoles	pulsed quadrupoles	pulsed quadrupoles	N/A	Pol.	pC quasi-elast.	5 min.
KEK PS	corr. dipoles	pulsed quadrupoles	pulsed quadrupoles	N/A	Pol.	pC & pp elastic	2 min.
AGS (1983-1988)	94 corr. dipoles	10 puls. quadrupoles	10 puls. quadrupoles	N/A	Pol.	pC & pp elastic	10 min.
AGS (1994-2002)	5% solenoid snake	vertical rf dipole	Did nothing	Did nothing	Beam/Pol.	pC & pp elastic	1 min.
Plan 1	**5% helical snake**	**vertical rf dipole**	**Intr. spin matching pulsed quadrupoles**	**N/A**	**Beam/Pol.**	**pC CNI**	**5 sec.**
Plan 2	25% helical snake	25% helical snake	25% helical snake	N/A	Beam	pC CNI	5 sec.

I. Other Possible Future Experiments with Michigan Ultra-Cold Jet or Solid PPT

Other possible scattering experiments using the Michigan Ultra-cold Jet or Solid PPT include:

- SPIN@RHIC: Polarized *p-p* Inclusive and Elastic A_n at 100-250 GeV RHIC (**Jet**); [23,30]
- SPIN@Fermilab: Polarized *p-p* Elastic A_n and A_{nn} at 120 GeV Main Injector (**Solid PPT**);
- SPIN@HERA: Polarized *p-p* Inclusive and Elastic A_n at 920 GeV HERA (**Jet**);
- NEPTUN-A: High-$P_\perp^2$ *p-p* Elastic A_n at 400 GeV UNK (on long-term standby status) (**Jet**).

J. Students and Symposia

The Spin Physics Center has three Michigan thesis students: V.S. Morozov, M. A. Leonova and C. C. Peters. The Center has also had 17 undergraduate students during the years 2002-2003.

The Center helped organize and/or sponsor a number of Symposia and Workshops including:

1. Spin and QCD Workshop, Virginia (April 2002)
2. 15th International Spin Physics Symposium, Brookhaven (September 2002)
3. Polarized Electron Source Workshop, MIT (September 2002)
4. Workshop on Increasing the AGS Polarization, Spin Physics Center, Michigan (November 2002)
5. Spin-Praha-2003 Advanced Study Institute, Prague, CZECH REPUBLIC (July 2003)
6. 10th Workshop on High Energy Spin Physics, Dubna, RUSSIA (September 2003)
7. 10th Workshop on Polarized Sources & Targets, Novosibirsk, RUSSIA (September 2003)
8. 9th Workshop on Polarized Solid Targets, Bad Honeff, GERMANY (October 2003)
9. 16th International Spin Physics Symposium, Trieste, ITALY (September 2004)

K. Michigan Spin Physics Center Staff

16 June 2003

Faculty:	A.D. Krisch, W. Lorenzon, V.K. Wong
Adjunct Faculty:	A.W. Chao, E.D. Courant, Ya.S. Derbenev, D.W. Sivers
Research Scientists:	A.M.T. Lin, V.G. Luppov , R.S. Raymond
Postdoctoral Fellow:	K. Yonehara
Consultants:	G.R. Court, D. Kleppner, D.C. Peaslee
Graduate Students:	M.A. Leonova, V.S. Morozov, C.C. Peters
Undergrad Students:	M.C. Kandes, C.B. Simmons, D.L. Sisco, D.R. Southworth
Secretarial Staff:	D.A. Walls, M.A. Zavala

L. Publications, Invited Lectures, Contributions, Books, *etc.* (2002-2003)*

Published or Submitted Manuscripts

1. *Spin flipping polarized electrons*, V.S. Morozov *et al.*, Phys. Rev. ST-AB **4**, 104002 (2001). *late 2001
2. *99.6% Spin-Flip Efficiency in the Presence of a Strong Siberian Snake*, B.B. Blinov et al., Phys. Rev. Lett. **88,** 014801 (2002).
3. *First spin flipping of a stored polarized deuteron beam*, V.S. Morozov *et al.*, accepted by Phys. Rev. Lett., subject to corrections.
4. *Vector and tensor polarization lifetimes for a stored deuteron beam*, B. v.Przewoski *et al.*, accepted by Phys. Rev. E.
5. *Spin manipulation of 1.94 GeV/c polarized protons stored in COSY*, V.S. Morozov *et al.*, to be submitted to Phys. Lett.

Manuscripts being Prepared

6. *Spin-flipping 850 MeV polarized electrons*, M.A. Leonova *et al.*, in preparation for Phys. Rev. ST-AB.
7. *Spin flip with an exactly 100% Siberian snake*, V.S. Morozov *et al.*, in preparation for Phys. Rev. Lett.
8. *Higher order snake depolarizing resonances*, B.B. Blinov *et al.*, in preparation for Phys. Rev. ST-AB.

Invited Lectures, Colloquia, Seminars and Presentations

9. *Violent Collisions of Spinning Protons*, Seminar for Michigan REU Students, A.D. Krisch (June 5, 2002).
10. *Violent Collisions of Spinning Protons: Past, Present and Future*, Colloquium at Köln Univ., GERMANY, A.D. Krisch (25 Apr 2003).
11. *Polarized Hadron Beams: Past, Present and Future*, Invited Lecture at COSY Annual Users Meeting, Bad Honeff, GERMANY, A.D. Krisch (15-16 Dec 2003)

NOTE: Many weekly Spin Physics Seminars at Michigan by members of the Spin Physics Center are not listed.

Conference Contributions and Proceedings

12. *99.9% Spin-Flip Efficiency in the Presence of a Strong Siberian Snake*, V.S. Morozov *et al.*, 15th Int'l Spin Physics Symposium, Brookhaven National Lab (2002), American Inst. of Physics Conf. Proc. **665**.
13. *Spin flipping and polarization lifetimes of a 270 MeV deuteron beam*, V.S. Morozov *et al.*, *ibid.*
14. *SPIN@U-70: An Experiment to Measure the Analyzing Power A_n in Very-high-$P_\perp^2$ p-p Elastic Scattering at 70 GeV*, V.G. Luppov *et al.*, *ibid.*
15. *Status of the University of Michigan Polarized Proton Target*, R.S. Raymond *et al.*, *ibid.*
16. *Polarized Atomic Hydrogen Beam Tests in the Michigan Ultra-Cold Jet Target*, K. Yonehara *et al.*, *ibid.*
17. *SPIN@U-70 Experiment,* A.D. Krisch *et al.*, Japan 50 GeV PS Workshop, Kyoto, JAPAN (Sept. 2002).
18. *Spin Manipulation of Polarized Protons and Deuterons at IUCF*, V.K. Wong *et al.*, CSS 2002 Workshop on COSY Physics, Jülich, GERMANY (September 2002)
19. *Status of the Michigan Ultra-Cold Polarized Hydrogen Jet Target*, V.G. Luppov *et al.*, Int'l Workshop on Polarized Sources and Targets "PST 2001", Nashville, Indiana (September 2001), eds. V.P. Derenchuk and B. von Przewoski, World Scientific, 32 (2002).
20. *Status of the Michigan Polarized Proton Target*, D.G. Crabb *et al.*, *ibid*, 126 (2002).
21. *Present status of the Michigan Hydrogen Gas Jet Target*, K. Yonehara *et al.*, Proc. 8th CIPANP, New York (May 2003), to be published.
22. *Spin-Flipping Polarized Deuterons at COSY*, K. Yonehara *et al.*, *ibid.*

Books

23. *Proceedings of Workshop on Increasing the AGS Polarization*, Ann Arbor, November 2002, American Inst. of Physics Conf. Proc. **667**, eds. A. D. Krisch, A. M. T. Lin, and T. Roser , AIP, New York (2003).

Popular Articles

24. *99.9% Spin-flip Efficiency*, CERN Courier **42**, No. 2, p. 6 (April 2002).

M. Recent Proposals

25. SPIN@J-PARC LoI: Tokai, JAPAN [Solid PPT] (Submitted December 2002)
26. SPIN@COSY 2: Jülich, GERMANY (Approved April 2003)
27. SPIN@COSY: Jülich, GERMANY (Approved December 2002)
28. SPIN@U-70: IHEP-Protvino, RUSSIA [Solid PPT] (Approved February 2001)
29. CE-83: IUCF (Approved May 2000)
30. SPIN@RHIC: Brookhaven (Rejected October 1997 and April 2000)

PART B

FINAL REPORT TO U.S. DEPARTMENT OF ENERGY

Office of Science
Grant DE-FG02-94ER40813
Spin Physics Center
University of Michigan

The Spin Physics Center's research, during 1 November 1993 until October 31, 2003, which was supported by earlier parts of this Grant is described in pages 1-55 of Part B. Part B also describes its research during about July 1964 until October 31, 1993, which was supported by an AEC/ERDA/DoE Contract.

9 February 2001

PROPOSAL TO U.S. DEPARTMENT OF ENERGY

Spin Physics Center University of Michigan

The High Energy Spin Physics Group at the University of Michigan has mostly studied large-$P_\perp^2$ proton-proton scattering since the 1960's. We obtained several significant early results including:

- first detailed 180° $\pi^-- p$ elastic data (ZGS 1966);
- first evidence for inner structure in the proton (ZGS 1966);
- first inclusive data (ZGS 1967);
- first evidence for Feynman-Yang inclusive scaling (ISR 1971).

Starting around 1970, we began to study the spin dependence of proton-proton collisions by building state-of-the-art polarized proton targets and helping to develop polarized proton beams. Using these polarized beams and targets, we obtained several significant results:

- the world's first accelerated polarized proton beams at the ZGS (1973) and then at the AGS (1984);
- unexpected large spin effects in the proton-proton total cross-section (ZGS 1974);
- set a limit on T-violation in 6 GeV $p-p$ elastic scattering at medium $P_\perp^2$ (ZGS 1977);
- large and totally unexpected two-spin effects in violent proton-proton elastic collisions (ZGS 1977-78);
- large two-spin effects in $n-p$ elastic scattering (ZGS 1979);
- large PQCD-violating one-spin effects in violent proton-proton elastic collisons (AGS 1985).

During the period 1989-2000, we focused on three major efforts:

1. Experiments on the one-spin asymmetry A_n in high energy $p-p$ collisions:
   a. AGS E-794: A_n in 24 GeV $p-p$ elastic scattering at high $P_\perp^2$
   b. NEPTUN-A: A_n in 400 GeV $p-p$ elastic scattering at UNK in IHEP-Protvino (on standby status)
   c. PROZA and RAMPEX: A_n in 70 GeV $p-p$ interactions at U-70 in IHEP-Protvino, Russia
2. Research and development on TeV polarized proton beams using Siberian snakes:
   a. Siberian snake experiments at the IUCF Cooler Ring
   b. Design of polarized beam capability for: the SSC; the Main Injector and Tevatron (partly funded by Fermilab); and HERA (partly funded by DESY); MIT-Bates new 1 GeV polarized electron ring (partly funded by MIT)
3. Research and development of state-of-the-art spin-polarized solid and gas jet targets:
   a. Solid NH_3 Michigan Polarized Proton Target (PPT) used at the AGS with 10^{11} s^{-1} beam intensity
   b. Michigan Ultra-cold Spin-polarized Atomic-hydrogen Jet (being commissioned).

Some of our more significant results during this period are:

- first demonstration of the Siberian snake concept (IUCF 1989)
- development of world-class PPT with 96% proton polarization with 10^{11} s^{-1} beam intensity (AGS 1989)
- precise confirmation of large PQCD-violating A_n asymmetry in violent $p-p$ collisions (AGS 1990)
- development of high-efficiency spin-flipping using rf solenoids and dipoles (IUCF 1994-2000)
- first observation of snake depolarizing resonances (IUCF 1997-2000)
- new Michigan Ultra-cold Polarized Jet reached 1.5 10^{15} s^{-1} spin-polarized H^0 atoms (SPC 2000).

In November 1998, we became the Spin Physics Center with established world-class expertise and resources in: polarized scattering experiments; solid and jet polarized proton targets; polarized proton and electron beams; and accelerator theory.

During 2001 to 2005, we plan to:

- measure A_n in very-large-$P_\perp^2$ elastic $p-p$ scattering at 70 GeV (SPIN@U-70), using our Solid PPT;
- continue developing and improving the state-of-the-art Michigan Ultra-cold jet polarized proton target, and possibly use it in another experiment, while NEPTUN-A is on standby status;
- continue the highly successful Siberian snake and spin-flipping experiments at IUCF through 2002;
- study polarized deuteron beam behavior in CE83 at IUCF, using Siberian snakes and spin-flipping;
- help to develop various polarized electron beam capabalities, including spin-flipping, at MIT-Bates;
- move our Siberian snake and spin-flipping studies to either MIT-Bates or COSY in 2003.

Our recently-tenured colleague, W. Lorenzon, will continue his NSF-supported research in HERMES at DESY.

Contents

A EARLY HISTORY (1964-1988)

A.1 Review of the 1960's

Our first experiment at the Argonne ZGS started taking data in 1965. We measured $\pi^- - p$ elastic scattering at 180° while varying the incident π^- energy.[a] We found considerable structure in the 180° differential elastic cross-section as a function of the incident energy as shown in Fig. A1; this structure appeared to be related to the formation of the various N* resonances. Apparently the amplitude for the intermediate state production of some resonances interfered quite strongly with the non-resonant elastic amplitude. The dramatic destructive interference found at 2.15 GeV was especially interesting; this was clearly associated with the N*(2190) resonance.

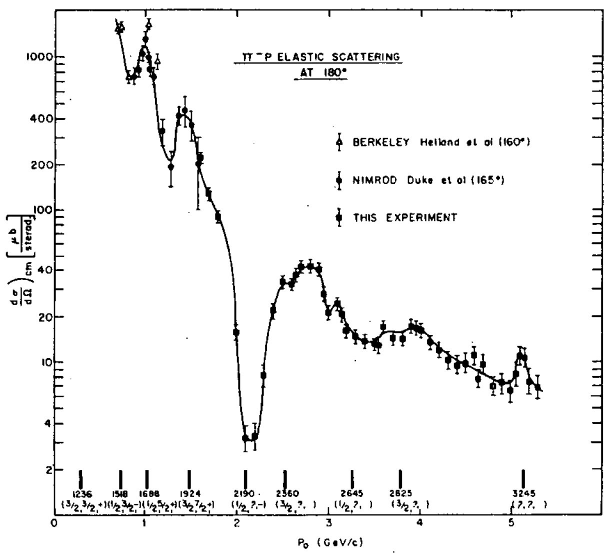


Fig. A1 Plot of $d\sigma/d\Omega$ against the incident π laboratory momentum, for $\pi^- p$ elastic scattering at 180°. The various N^* resonances are shown.[a]

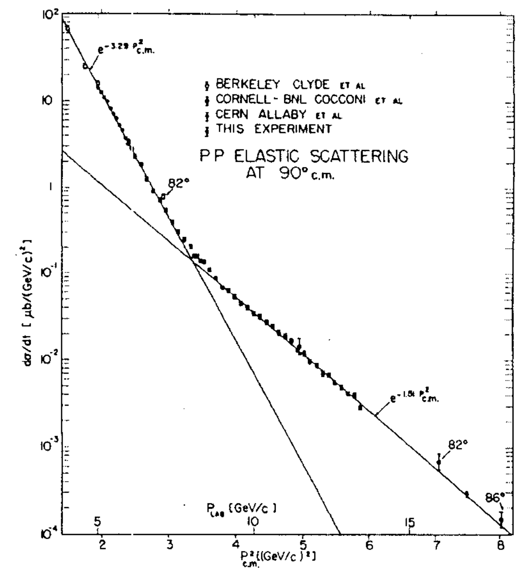


Fig. A2 Plot of $d\sigma/dt$ vs. P_{cm}^2 for $p-p$ elastic scattering at 90°_{cm}. The two different regions suggest structure inside the proton.[b]

Later in 1966, we measured proton-proton elastic scattering at 90° in the center-of-mass at closely spaced P_{lab} values from 5.0 to 13.4 GeV/c.[b] Fig. A2 shows the elastic differential cross-section at 90°_{cm} plotted against P_{cm}^2 which is equivalent to $P_\perp^2$. Two straight lines fit the data rather well; the sharp change of slope suggested structure within the proton. This structure was interpreted as being due to inner regions of the proton with different opacities; the New York Times on November 22, 1966 labeled this the "Onion" model. The sharp break was probably the first direct evidence for the proton's constituent quarks which were later seen more clearly in the SLAC deep inelastic scattering experiments.

In 1967, we used particle identity to plot[c] all existing high energy p-p elastic scattering data against a Lorentz-contracted $P_\perp^2$ variable, $\beta^2 P_\perp^2$. As shown in Fig. A3, the data was well fit by three straight lines in the logarithmic plot of the elastic cross-sections spanning twelve decades. These three lines were interpreted as being due to three Gaussian regions in the proton-proton interaction (the onion model).

Also in 1967, we made the first systematic measurements of what Feynman later named inclusive cross-sections[d]. We studied the inelastic particle production cross-section for $A + B \to C + Anything$ in the center-of-mass system in high energy proton-proton collisions and introduced the "inclusive" c. m. variables, $P_\perp$ and P_l, to parameterize particle production. Feynman later showed that $x = P_l/P_{c.m.}$ was an even better variable. We saw a clear Gaussian dependence on the $P_\perp$ of the produced particles as shown in Fig. A4. We studied inclusive cross-sections in more detail[e] in 1968 and 1969 as their theoretical interest grew rapidly; Feynman and Yang led this theoretical effort.

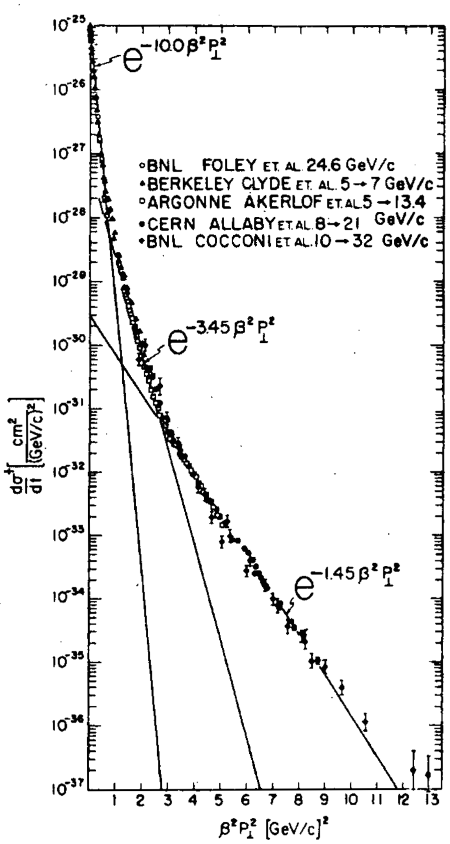


Fig. A3 Plot of the particle-identity-modified cross-section $d\sigma^\dagger/dt$ vs. $\beta^2 P_\perp^2$ for all high-energy $p-p$ elastic scattering data existing in 1967.[c]

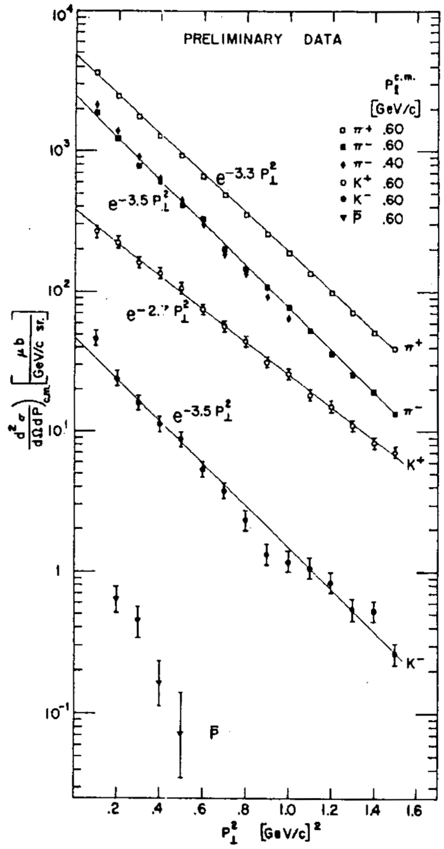


Fig. A4 Plot of $(d^2\sigma/d\Omega dp)_{cm}$ against $P_\perp^2$ for $\pi^\pm$, $K^\pm$ and $\overline{p}$ production in 12.5 GeV/c $p-p$ collisions with P_l held fixed in the cm[d].

A.2 Review of the 1970's

In 1971, we made the first measurement of TeV proton-proton inclusive cross-sections at the CERN ISR.[f] Fig. A5 shows the invariant cross-section $Ed^3\sigma/dP^3$ plotted against the Feynman variable $x = P_l/P_{c.m.}$ for various $P_\perp^2$ values. Notice that our ISR data, at an equivalent E_{lab} of 500 to 1500 GeV, fell exactly on top of the earlier low energy data at 12 to 24 GeV when the "invariant" cross-section $Ed^3\sigma/dP^3$ was plotted against x and $P_\perp^2$ as predicted by Feynman and Yang. This was the first experimental evidence for Feynman-Yang scaling.

During 1969 to 1973, we played a leading role in accelerating the world's first high energy polarized proton beam at the ZGS, which is shown in Fig. A6. In 1975 we published the long detailed paper "Acceleration of Polarized Protons to 8.5 GeV/c",[g] which described how the ZGS's depolarizing resonances were overcome. This accelerated polarized beam opened a new area of high energy physics and was instrumental in extending the operation of the ZGS from 1975 until 1979.

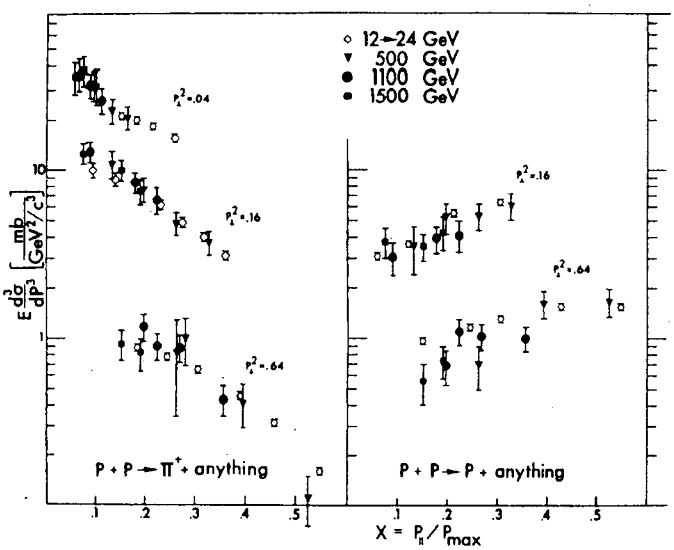


Fig. A5 Plot of $Ed^3\sigma/dP^3$ vs. x with $P_\perp^2$ held fixed for inclusive π^+ and p production.[f]

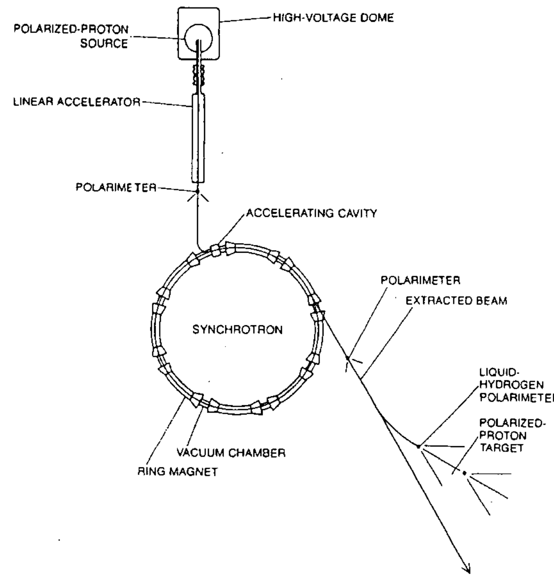


Fig. A6 The components needed to accelerate polarized protons in the Zero Gradient Synchrotron.[l]

Starting around 1973, our group began extensive measurements of spin-dependent cross-sections using the ZGS polarized beam and a polarized proton target built at Michigan. In 1973 and 1975, we made the first measurements of spin-antiparallel and spin-parallel total cross-sections.[h] As shown in Fig. A7, we found significant differences between the two transverse-spin p-p total cross-sections at energies between 2 and 6 GeV. This unexpected spin cross-section difference led to many experiments studying the "dibaryon" phenomenon. We continue to feel that these large spin effects are probably due to the threshold for N^* resonance production.

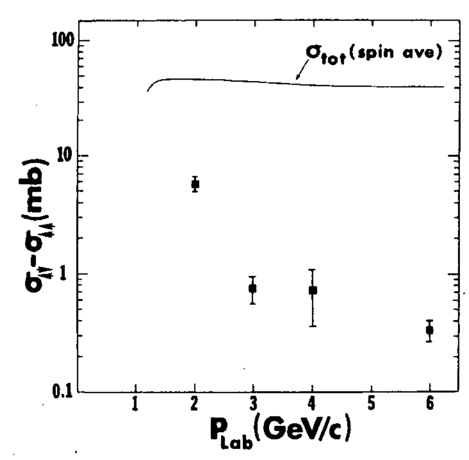


Fig. A7 The difference between the spin-antiparallel and spin-parallel total $p-p$ cross-sections is plotted against the incident beam momentum.[h]

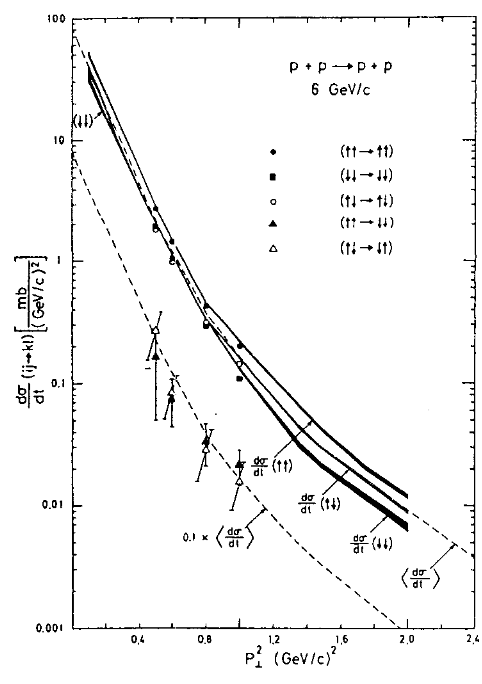


Fig. A8 The four-spin cross-sections $d\sigma/dt(ij \to kl)$ and the two-spin $d\sigma/dt(ij)$ are plotted vs. $P_\perp^2$ for $p-p$ elastic scattering at 6 GeV/c.[i]

Our group studied in great detail the spin dependent p-p elastic cross-sections. We even obtained pure-spin cross-sections by measuring the polarization of each recoil proton by scattering it on a carbon target.[i] Fig. A8 shows the two-spin and the four-spin cross-sections for p-p elastic scattering at 6 GeV/c plotted against $P_\perp^2$. Note that the different spin states have quite unequal cross-sections at large $P_\perp^2$ and that the double-spin-flip cross-sections are about 10% of the non-flip cross-sections. This difficult experiment also provided evidence for time reversal invariance in strong interactions.

Our most interesting result was a large and unexpected difference [j] between the spin-parallel and spin-antiparallel p-p elastic scattering cross-sections found at large-$P_\perp^2$. The dramatic difference between the spin-parallel and spin-antiparallel cross-sections at large-$P_\perp^2$ is shown in Fig. A9. Note that the spin-parallel cross-section at large-$P_\perp^2$ has the same hard-scattering slope of 1.6 $(\mathrm{GeV/c})^{-2}$ which is seen at very high energies, while the spin-antiparallel cross-section drops much more rapidly. This data suggested that spin somehow plays a dominant role in the violent (large-$P_\perp^2$) collisions of the proton's constituent "quarks" which themselves should each have spin 1/2.

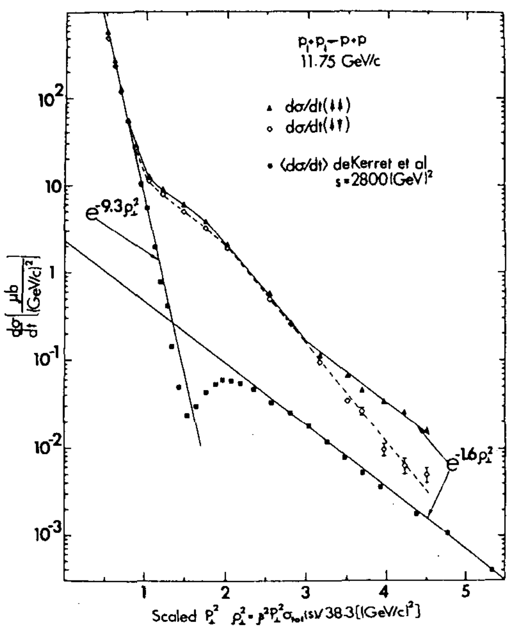


Fig. A9 The spin-dependent p-p elastic cross-sections at 11.75 GeV/c and spin-averaged cross-section at $s = 2800$ GeV^2 are plotted against the scaled $P_\perp^2$ variable.[j]

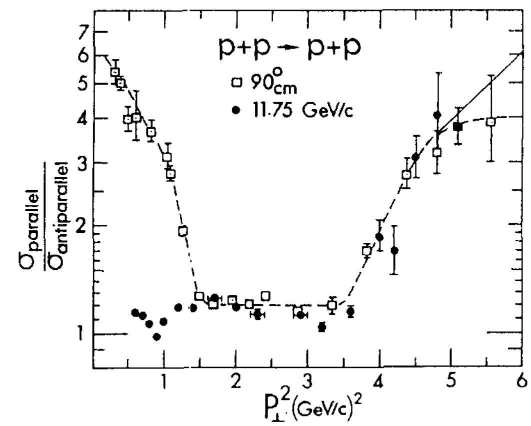


Fig. A10 The ratio of spin-parallel to spin-antiparallel p-p elastic cross-sections is plotted vs. $P_\perp^2$ for the fixed angle of 90°_{cm} [k] and for the fixed energy of 11.75 GeV/c.[j]

Bethe and Weisskopf then pointed out that this large spin difference could be due to particle identity effects near the special point of 90°_{cm}. To resolve this issue, we measured the energy dependence[k] of the spin-spin effect in high-$P_\perp^2$ p-p elastic scattering at 90°_{cm}. Fig. A10 compares the $P_\perp^2$ dependence of the ratio of spin-parallel to spin-antiparallel p-p cross-sections in two cases: holding the c. m. angle fixed at 90°; and holding the incident momentum fixed at 11.75 GeV/c. Notice that both sets of data essentially fall on top of each other at $P_\perp^2$ above 1.5 $(\mathrm{GeV/c})^2$, and that both rise sharply above 4 $(\mathrm{GeV/c})^2$. This demonstrated that the large spin effect shown in Fig. A9 is a large-$P_\perp^2$ effect and not a 90°_{cm} particle identity effect.

A popular presentation of these polarized beam and polarized target experiments appeared in Scientific American in 1979.[l] The article discussed the large and unexpected spin forces, the Michigan polarized proton target and the ZGS polarized proton beam, which was shown in Fig. A6.

We also investigated the scattering of 6 GeV/c polarized neutrons by accelerating a polarized deuteron beam to 12 GeV/c and then scattering it on a polarized proton target.[m] We found large spin-spin effects in n-p elastic scattering which are quite different from those in p-p elastic scattering as shown in Fig. A11. The large negative value of A_{nn} for n-p scattering was not expected; earlier Regge model predictions were inconsistent with the data.
The ZGS was closed down on October 1, 1979 after several years of essentially dedicated polarized proton beam operation. The ZGS polarized beam program was summarized in an Annual Review of Nuclear and Particle Science article.[n]

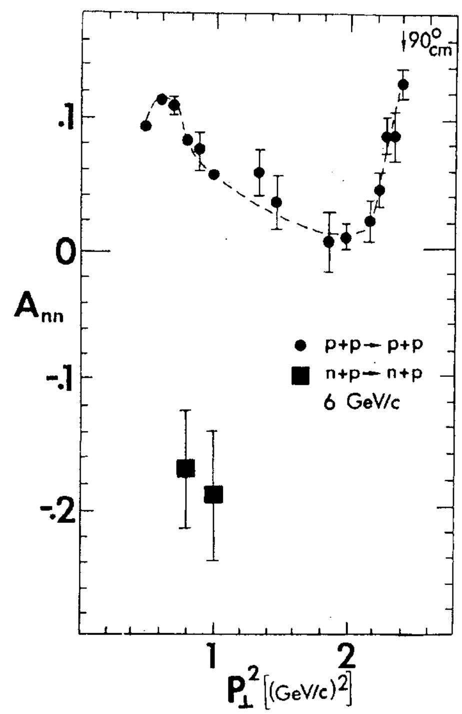


Fig. A11 The spin-spin correlation parameter, A_{nn}, plotted against $P_\perp^2$ for $n-p$ and $p-p$ elastic scattering at 6 GeV/c.[m]

A.3 Review of the 1980's

Starting in the late 1970s, Michigan led the project to accelerate a polarized proton beam in the Brookhaven AGS. We first organized the Ann Arbor Workshop on Higher Energy Polarized Beams in 1977.[o] We next actively participated in the 1978 Brookhaven Summer Study on the AGS polarized beam[p], and then had a major responsibility for the AGS polarized beam project. Since the AGS is a strong focusing machine with a higher energy than the ZGS, it was more difficult to overcome the many strong AGS depolarizing resonances. Constructing and commissioning the 22 GeV/c AGS polarized proton beam were described extensively in a 1989 Physical Review paper[q] based on the Michigan thesis of F.Z. Khiari. The main modifications required for polarized beam acceleration at the AGS are shown in Fig. A12. Michigan built the pulsed quadrupoles as well as the internal and high-energy polarimeters; we also led the difficult but successful commissioning.

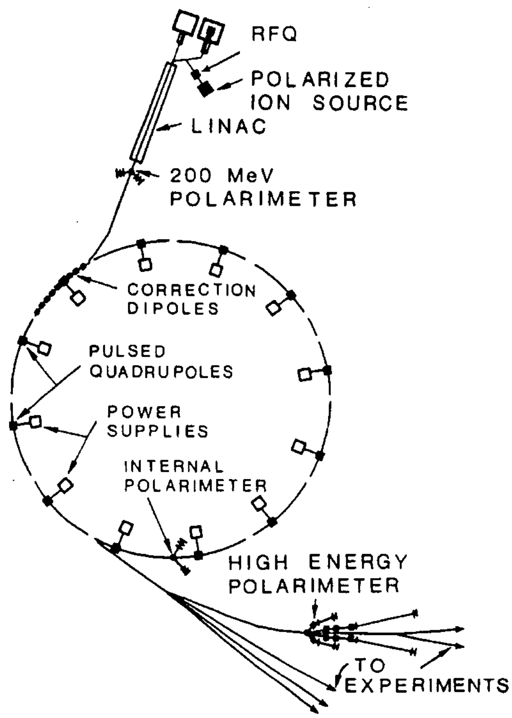


Fig. A12 Layout of the AGS for the operation of the polarized proton beam.[q]

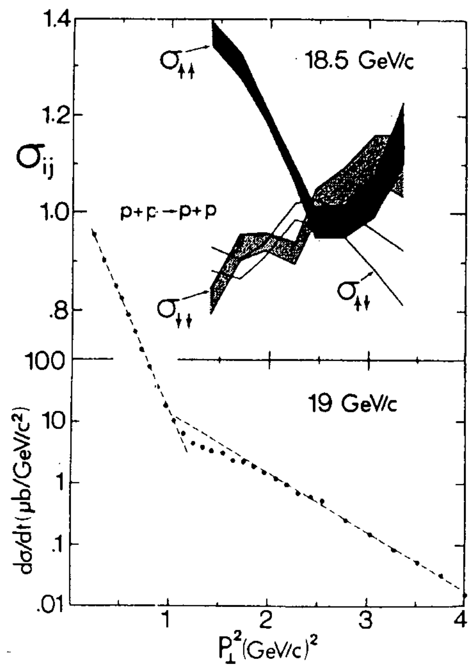


Fig. A13 The relative pure-initial-spin 18.5 GeV/c elastic cross-sections are plotted against $P_\perp^2$ for spin-parallel-up, spin-parallel-down and spin-antiparallel scattering.[r]

We then measured spin-spin effects in p-p elastic scattering with the AGS polarized proton beam at 16.5 and 18.5 GeV/c.[q,r] Fig. A13 shows the relative pure-initial-spin-state cross-sections plotted against $P_\perp^2$. Notice the rapid variations in the three different spin cross-sections; this spin dependence may somehow be associated with the structure in the spin-average cross-section which is also shown.

Starting in 1982, we began measuring the one-spin dependence of p-p elastic scattering near 28 GeV by scattering the AGS unpolarized proton beam from a polarized proton target.[s] We found a large and totally unexpected one-spin asymmetry, A, at large $P_\perp^2$. This surprising result did not agree with then-existing PQCD calculations and caused some controversy. With a much improved polarized target, the experimental result was confirmed with high precision in 1990[t]; this data is discussed in Section **B1** and shown in Fig. B1.

The controversy about the large-$P_\perp^2$ one-spin asymmetry's disagreement with PQCD led to another Scientific American article in 1987[u] which discussed both the two-spin data from the ZGS and AGS, and the one-spin data from the AGS. The article's Fig. A14 shows a 3-dimensional plot of the ratio of spin-parallel to spin-antiparallel cross-sections against the incident energy and $P_\perp^2$. The plot shows an unanticipated richness in the structure of spin-spin effects and their persistence to high energy and to high $P_\perp^2$.

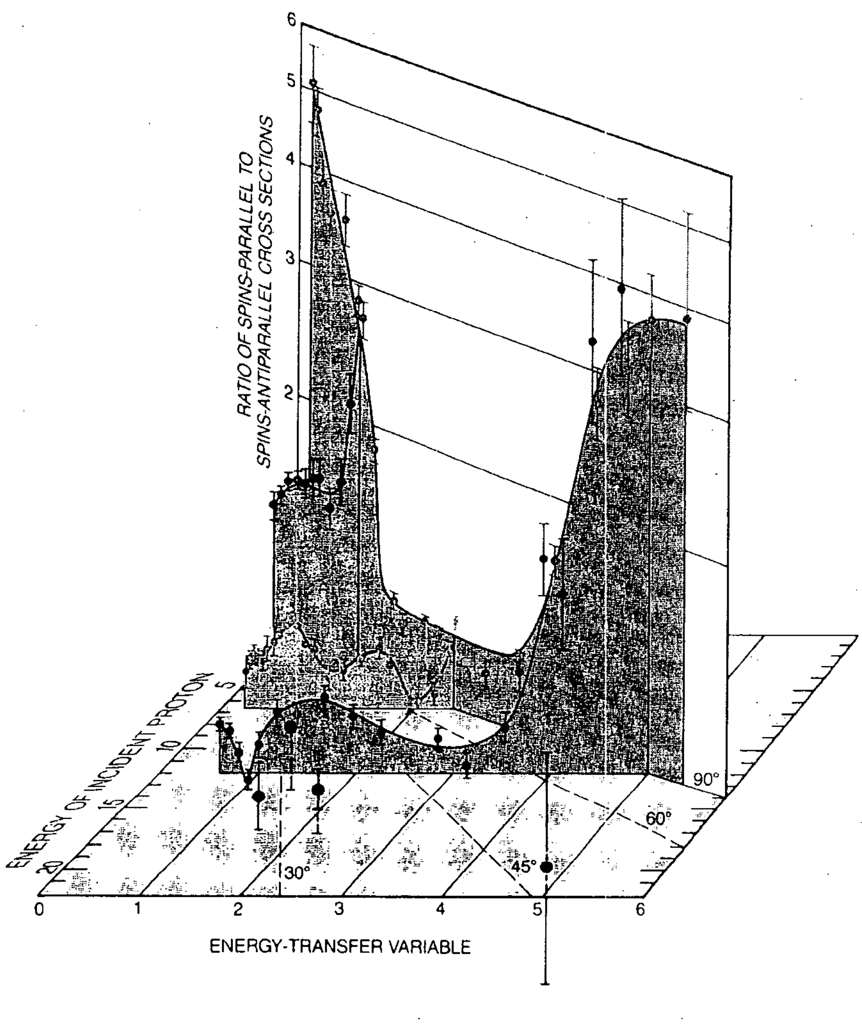


Fig. A14 A 3-dimensional plot of the spin-parallel to spin-antiparallel $p-p$ cross-sections ratio against the incident energy and energy transfer variable $P_\perp^2$.[u]

A.4 Selected Early References

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B RECENT HISTORY (1989-2000)

B.1 High-$P_\perp^2$ Spin Effects at AGS

Our 1990 AGS experiment measured with high precision the analyzing power A_n in proton-proton elastic scattering at 24 GeV. As shown in Fig. B1, it confirmed[6] the large and unexpected one-spin asymmetry found earlier[s]. These large and surprising non-zero A_n values did not agree with PQCD calculations at high-$P_\perp^2$ and caused some earlier controversy. This high precision confirmation apparently ended the experimental controversy. Nevertheless, the theoretical controversy continues; this experiment and several inelastic spin experiments have brought into question the range of validity of perturbative QCD, as discussed in Scientific American[l,u] and Physics Today‡.

The 1990 AGS experiment used the very successful Michigan Polarized Proton Target[3] and a high intensity AGS unpolarized proton beam of $10^{11}\,\mathrm{sec}^{-1}$. J.A. Stewart's thesis[205,222] contains a detailed description of the experiment and the 5 T at 1 K polarized proton target.

Our NEPTUN-A and now SPIN@U-70 experiments in Russia, which are described in Sections **B.7** and **C.1**, plan to determine if this surprising one-spin asymmetry persists to higher energy and, even more importantly, higher $P_\perp^2$.

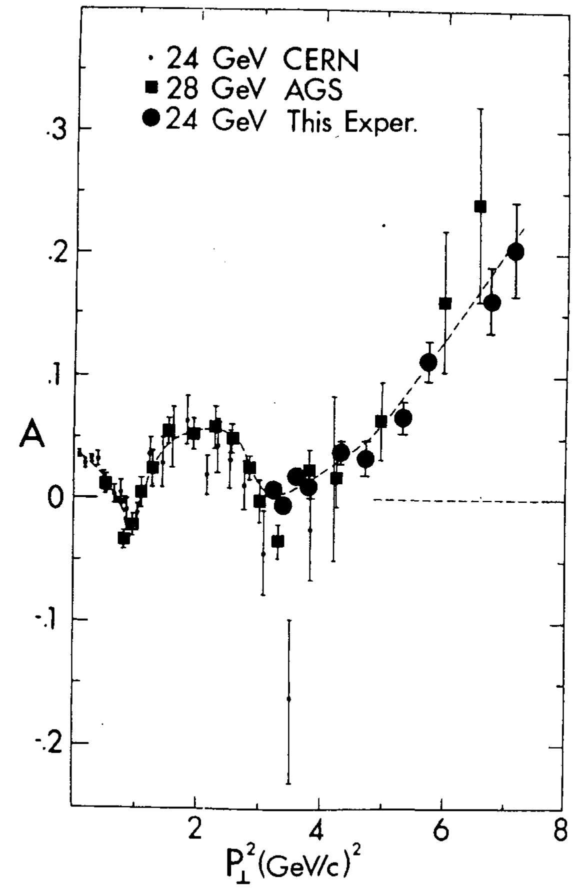


Fig. B1 The analyzing power, A_n, is plotted against $P_\perp^2$ for spin-polarized proton-proton elastic scattering at 24 and 28 GeV. [6]

B.2 Michigan Solid Polarized Proton Target

The Michigan 5 T at 1 K solid ammonia Polarized Proton Target (PPT), which is shown in Fig. B2, was unexpectedly successful.[3] With its cooling power of about 1 watt at 1 K, we were able to operate it in an AGS beam of over 2 10^{11} protons per pulse as we had anticipated. Our unexpected result was the 96% proton polarization in frozen ammonia at 5 T and 1 K. The polarization rise-time was also unexpectedly fast as shown in Fig. B3. The PPT was then reassembled in Ann Arbor in 1991 and is run about once a year,[168] sometimes along with D.G. Crabb (now at Virginia) to test some target materials[174] for his similar polarized target for experiments at SLAC and CEBAF. As discussed in Section **C.1**, our Solid PPT may be soon used in the 70 GeV large-$P_\perp^2$ proton-proton elastic A_n experiment SPIN@U-70 at IHEP-Protvino's U-70 accelerator.

‡ B. Schwartzchild, Physics Today p.17 August 1985.

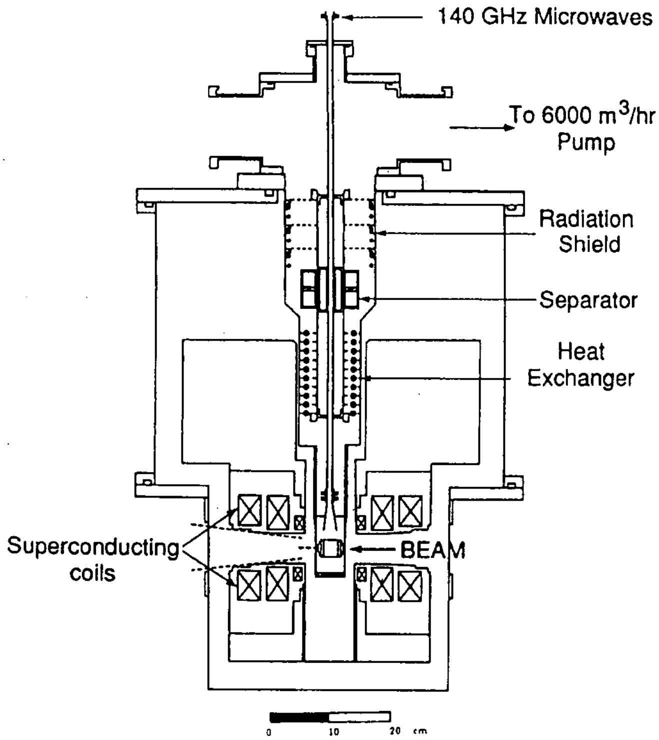


Fig. B2 The Solid Polarized Proton Target's superconducting magnet produces a highly uniform 5 T field; the He^4 cryostat produces about 0.9 W of cooling power at 1 K. The 140-GHz microwaves enter the small target cavity with irradiated NH_3 target material.[3]

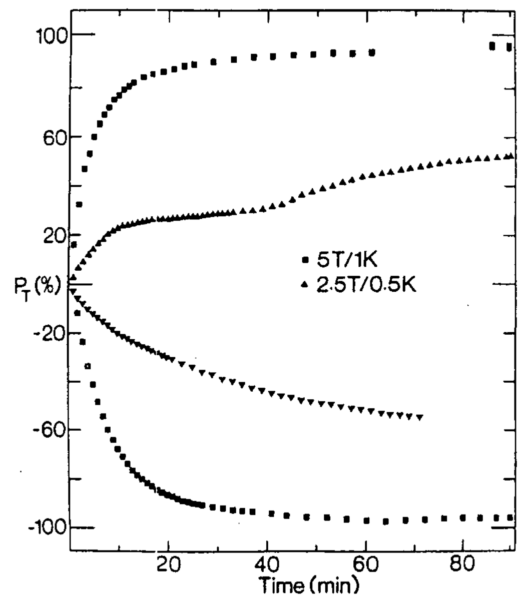


Fig. B3 The spin polarization of the free protons in NH_3 is plotted against the time of microwave irradiation. The data at 5 T and 1 K are compared with earlier data at 2.5 T and 0.5 K.[3]

B.3 Siberian Snake Experiments at IUCF

The Siberian snake experiments at the IUCF Cooler Ring [CE-05, CE-15, CE-20, CE-40, CE-57 and CE-69] have been unexpectedly successful.*,♯ A Siberian snake is a device which forces an accelerator ring's depolarizing fields to cancel themselves by rotating each proton's spin by 180° on each turn around the ring.

In 1985, we organized the Ann Arbor Workshop on Polarized Beams at the SSC.† This workshop concluded that the Siberian snake concept should soon be tested somewhere; we then chose to test the first Siberian snake in the IUCF Cooler Ring. As shown in Fig. B4, we constructed and installed a Siberian snake containing a 2 $T \cdot m$ superconducting solenoid magnet, which rotates the spin by 180°; the snake also contains eight quadrupole magnets which do nothing to the spin, but compensate the large orbit distortions caused by the strong solenoid.

* The FY 1993 NSF Budget submission to Congress listed our Siberian snake program as the highlight of the NSF High Energy and Nuclear Physics Program. (NSF funds IUCF).

♯ The NSF recently extended the operation of IUCF through the end of 2002.

† Workshop on Polarized Beams at the SSC, Ann Arbor 1985, edited by A.D. Krisch, A.M.T. Lin and O. Chamberlain, A.I.P. Conf. Proc. **145** (1986).

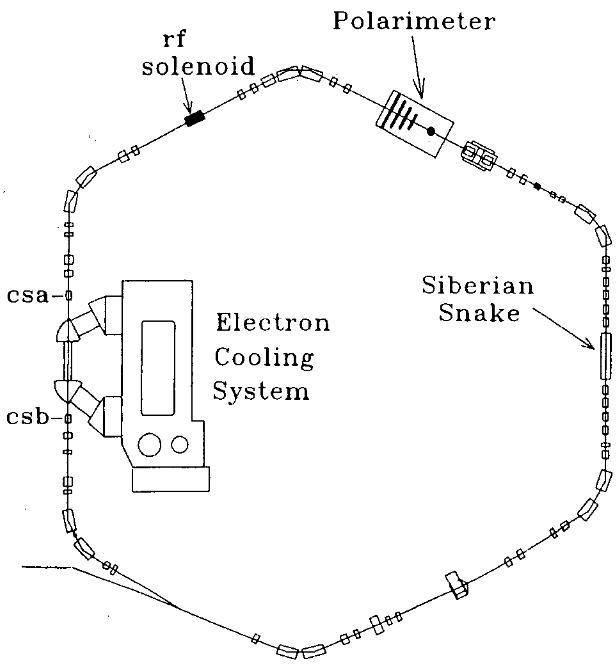


Fig. B4 The IUCF Cooler Ring. Note the injection kicker magnets, polarimeter, Siberian snake, rf solenoid and the csa/csb solenoids.[2]

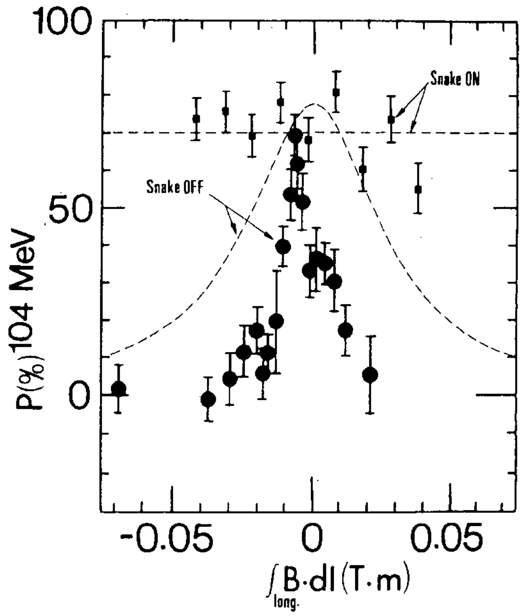


Fig. B5 Siberian snake overcoming the $G\gamma = 2$ imperfection resonance.[2]

In 1989, we first demonstrated[2] that the Siberian snake concept really works by studying the $G\gamma = 2$ imperfection resonance at 108 MeV; the measured beam polarization at 104 MeV is plotted against the imperfection magnetic field in Fig. B5. With no snake, there was a full polarization of about 70% only when we exactly corrected all imperfection fields; any imperfection field rapidly killed the polarization. However, with the Siberian snake on, there was full polarization over the entire range. The Siberian snake clearly overcame this imperfection resonance.

In 1990, we studied[4] an intrinsic depolarizing resonance which is caused by the vertical betatron oscillations that exist in all accelerators. This resonance occurs in the Cooler Ring when $G\gamma = \nu_y - 3$, where ν_y is number of vertical betatron oscillations in one turn around the Ring. The polarization at 177 MeV is plotted against ν_y in Fig. B6. With the snake off, the beam is totally depolarized at the resonant ν_y of 5.13. However, with the snake on, there is full polarization over the entire range. Thus the Siberian snake easily overcame this intrinsic depolarizing resonance.

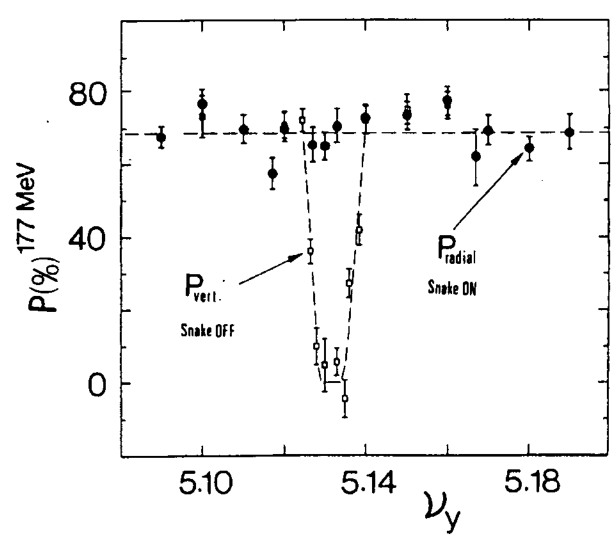
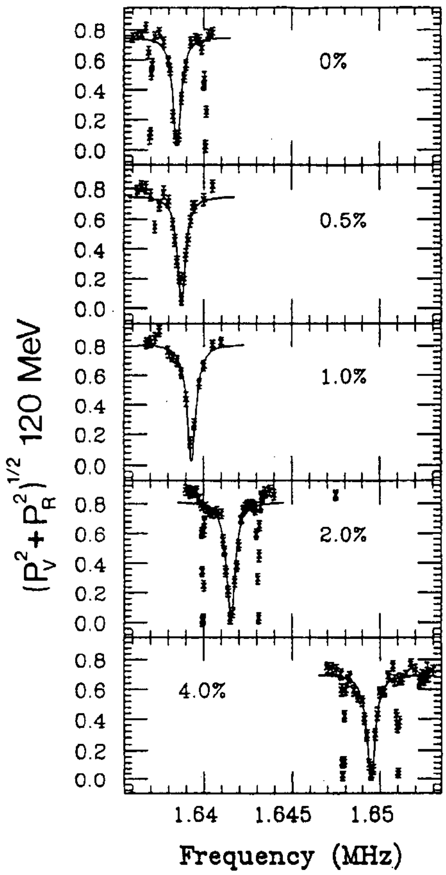


Fig. B6 Siberian snake overcoming the $G\gamma = \nu_y - 3$ intrinsic resonance.[4]

In 1990, CE-15 found that a Siberian snake could easily overcome a synchrotron depolarizing resonance.[4] These resonances, which are caused by synchrotron oscillations in the protons' energy, appear as narrow sidebands on each side of some depolarizing resonance. Some Synchrotron sideband resonances are shown in Fig. B7.

We also discovered a "Type-3" Siberian snake which was inadvertently built into the cooling section of the Cooler Ring.[9] Type-1 and Type-2 snakes rotate the spin around the longitudinal and radial directions, respectively, while a Type-3 snake rotates the spin around the vertical direction. A Type-3 snake can only exist because spin matrices do not commute.



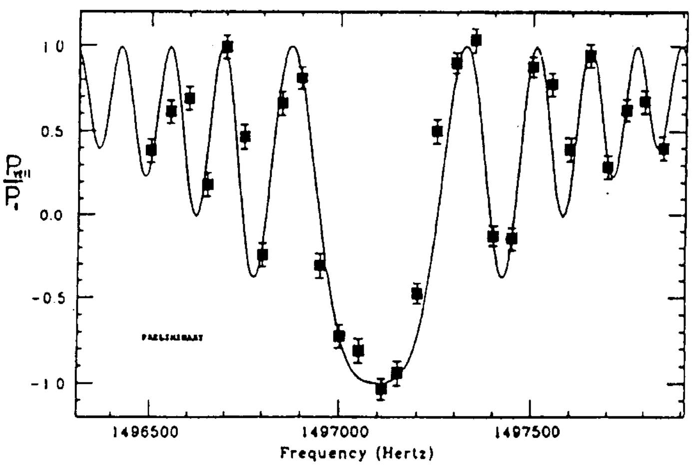


Fig. B8 The relative vertical beam polarization at 104 MeV is plotted against the rf solenoid frequency. The data fits a sinusoidal spin precession curve.[127]

Fig. B7 The measured transverse beam polarization is plotted against the frequency of the rf solenoid magnet for five different partial snake strengths.[14]

In 1992, CE-20 fabricated a 25 kV rf solenoid magnet using a spare ceramic vacuum pipe from the AGS pulsed quadrupoles. We used this to create and study the properties of an "rf induced" depolarizing resonance. We first studied the effect of a partial Siberian snake on an rf depolarizing resonance[14] by measuring the resonant frequency at different snake strengths, s. As shown in Fig. B7, the measured frequency of each dip's center increases with s; these measured resonant frequencies fit quite well the predicted behavior, which is almost quadratic.

We also found that when the rf was turned on for a fixed time, the spin precessed around some stable spin direction by a fixed angle.[127] This resulted in the now-understood sinusoidal spin precession curve shown in Fig. B8.

We successfully flipped the spin of a stored polarized proton beam[22] by ramping the rf solenoid frequency through the resonant frequency as shown in Fig. B9. This spin-flip capability should allow future experiments using stored polarized proton beams to strongly discriminate against most systematic errors by flipping the spin direction every few seconds.

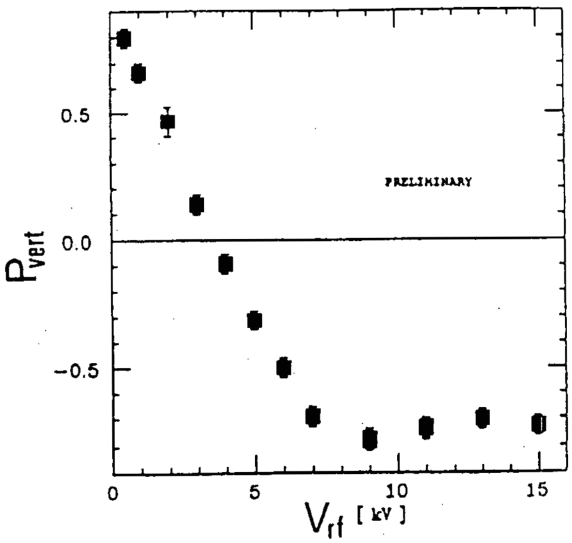


Fig. B9 The measured vertical beam polarization is plotted against the rf solenoid voltage, while ramping the frequency from 1.509 to 1.507 MHz. Full spin-flip occurs above 7 kV.[22]

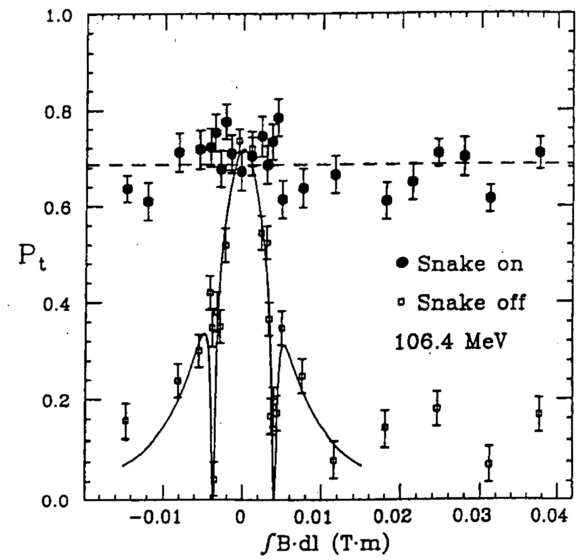
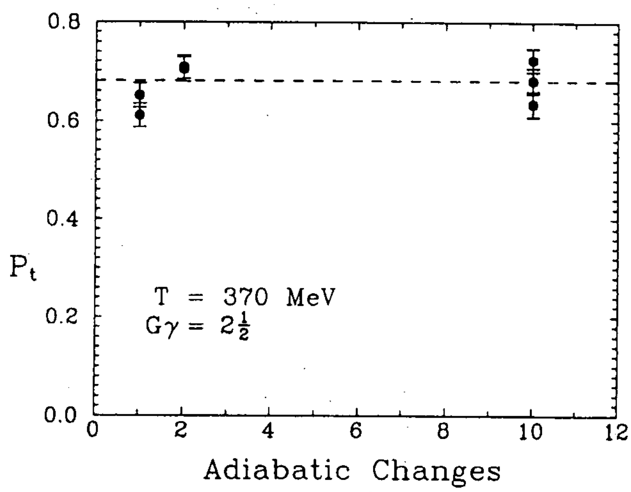


Fig. B10 Siberian snakes overcoming overlapping depolarizing resonances. With the snake off, the overlapping resonances cause sharp depolarizing dips. With the snake on, there is no depolarization.[15]

The behavior of "overlapping" depolarizing resonances was then studied[15] using a stored 106.4 MeV polarized proton beam and our new stronger rf solenoid magnet with a lower voltage but with a smaller diameter ceramic vacuum pipe. We created an "rf induced" depolarizing resonance, which we then forced to overlap with the $G\gamma = 2$ depolarizing resonance. We found significant interactions between the two resonances by varying their frequencies and strengths; the frequency of the rf resonance strongly affected the response of the imperfection resonance to correction magnetic fields. As shown in Fig. B10, there were strong interference dips as we varied the strength of the imperfection fields. When the Siberian snake was turned on, it overcame all observable depolarization due to the overlapping resonances and maintained full polarization over the entire range.

In 1994, CE-40 found no measurable depolarization of a 370 MeV stored polarized proton beam when we adiabatically turned a partial Siberian snake on and off a total of 10 times[19], as shown in Fig. B11. This 370 MeV energy corresponds to a spin tune of $G\gamma = 2.5$. This data confirmed the prediction that Siberian snakes can be safely turned on adiabatically at half-integer spin tune energies. This result has some significance for polarized beam acceleration at the Brookhaven AGS, the Fermilab Booster, and DESY's PETRA.



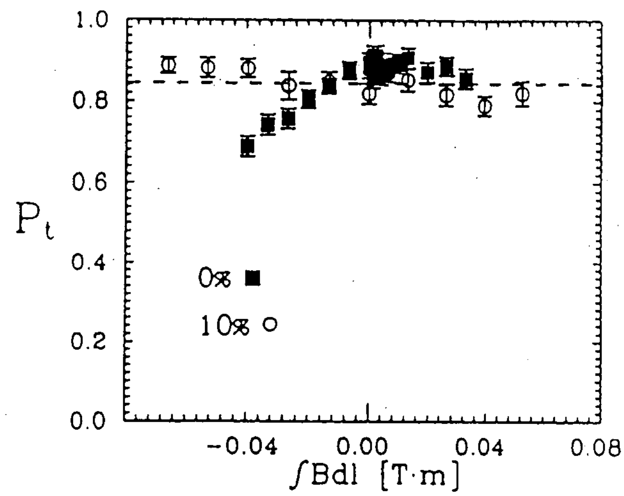


Fig. B11 The 370 MeV transverse polarization, $P_t = \sqrt{P_v^2 + P_r^2}$, is plotted against the number of times the 25% partial Siberian snake was turned on or off. The dashed line is the best fit to the data, which show no depolarization within our 2% precision.[19]

Fig. B12 The measured transverse polarization P_t, at 140 MeV, is plotted against the imperfection $\int B \cdot dl$ with no snake and with a 10% partial Siberian snake. The dashed line is a fit to the snake-on data. The beam was accelerated from 95 to 140 MeV.[21]

In 1994, we made the first test of a partial Siberian snake during polarized beam acceleration. By ramping our new warm solenoid magnets, we maintained a 10% partial snake while accelerating polarized protons from 95 to 140 MeV through the $G\gamma = 2$ imperfection depolarization resonance at 108 MeV. As shown in Fig. B12, the 10% snake suppressed all observable depolarizing effects.[21] The AGS later installed a partial Siberian snake and found similar results.

We were able to flip the spin direction of a 139 MeV stored polarized proton beam 50 times with no observable polarization loss within our 2% errors. By adjusting the ramp time, *the polarization loss was reduced to 0.0000 ± 0.0005 per spin-flip.*[22] This new spin-flip capability should allow experiments using stored polarized proton beams to discriminate strongly against most systematic errors.

The CE-57 experiment was approved in 1995 with high priority. Using a 160 MeV stored polarized proton beam and a 20% partial snake, we found clear evidence for the second-order $\nu_s = \nu_y - \nu_x + 1$ intrinsic depolarization resonance.[25] By changing the horizontal betatron tune by $\Delta\nu_x = 0.06$, we found that the vertical betatron tune ν_y of the narrow second-order depolarizing resonance shifted by almost exactly the same amount, as shown in Fig. B13. These weak second-order resonances should be considered when using a partial Siberian snake with a medium-energy polarized proton beam.

We then succeeded in forcing a 140 MeV polarized beam to cross several intrinsic depolarization resonances by varying a partial Siberian snake's strength for different values of the vertical and horizontal betatron tunes.[26] This new capability could be used in medium energy proton beams.

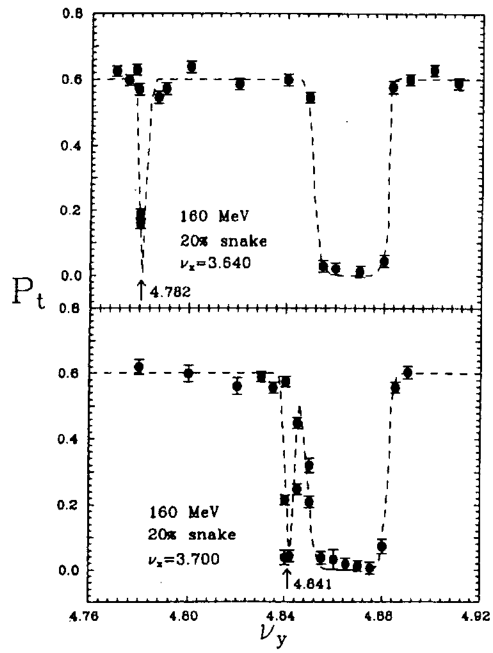


Fig. B13 The narrow dip's ν_y-shift of 0.059±0.001 is equal to the 0.060 change in ν_x, as predicted for the $\nu_s = \nu_y - \nu_x + 1$ second-order resonance.[25]

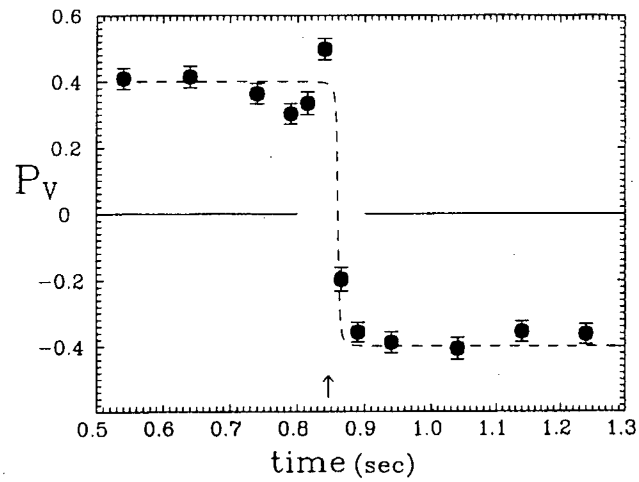


Fig. B14 The polarization spin-flips when the kicker is pulsed before crossing the resonance.[27]

In 1996, we accelerated a polarized beam from 95 to 380 MeV through both the $G\gamma$=2 imperfection resonance and the $G\gamma$ = 7 - ν_y intrinsic depolarizing resonance.[27,93] As expected, the beam spin-flipped during the imperfection resonance crossing and partially depolarized while initially crossing the intrinsic resonance. We then pulsed a vetical kicker magnet for 500 ns to increase the beam's vertical betatron amplitude, which stengthened the intrinsic resonance. By varying the start time of the pulse, we observed a sharp spin-flip due to crossing the strengthened intrinsic resonance, which preserved the beam's polarization, as shown in Fig. B14. This new alternative method of overcoming intrinsic depolarizing resonances should be useful for polarized beams in medium energy rings such as LISS and the injector rings at Brookhaven, UNK, Fermilab, DESY, and LHC.

Using a 104 MeV stored polarized proton beam and a full Siberian snake in the IUCF Cooler Ring, we made the first observation of a so-called higher-order "snake" depolarizing resonance.[28,94] A full Siberian snake forces the spin tune ν_s to be half-integer. If the vertical betatron tune ν_y is set near a quarter-integer, then the $\nu_s = n \pm 2\nu_y$ second-order snake resonance can depolarize the beam. With a full Siberian snake and ν_y = 4.756, we found the deep depolarization dip shown in Fig. B15; when ν_y was changed to 4.781, the deep dip disappeared. This confirmed that the deep dip was a "snake" depolarizing resonance.

Using an rf solenoid magnet, we studied the depolarization of a stored 104.1 MeV vertically polarized proton beam. As shown in Fig. B16, the two primary rf depolarizing resonances were properly centered around the protons' circulation frequency f_c, at $f_c(3-\nu_s)$ and $f_c(\nu_s - 1)$, where ν_s is the spin tune. Moreover, each resonance was roughly consistent with the expected width of about 720 Hz. Each primary rf resonance had two synchrotron sideband resonances at the expected frequencies. The two $\nu_s - 1$ sidebands were deep dips while the two $3 - \nu_s$ sidebands were very shallow; this was not expected. Moreover, all four sideband frequencies were unexpectedly wider than the two primary resonances.[33]

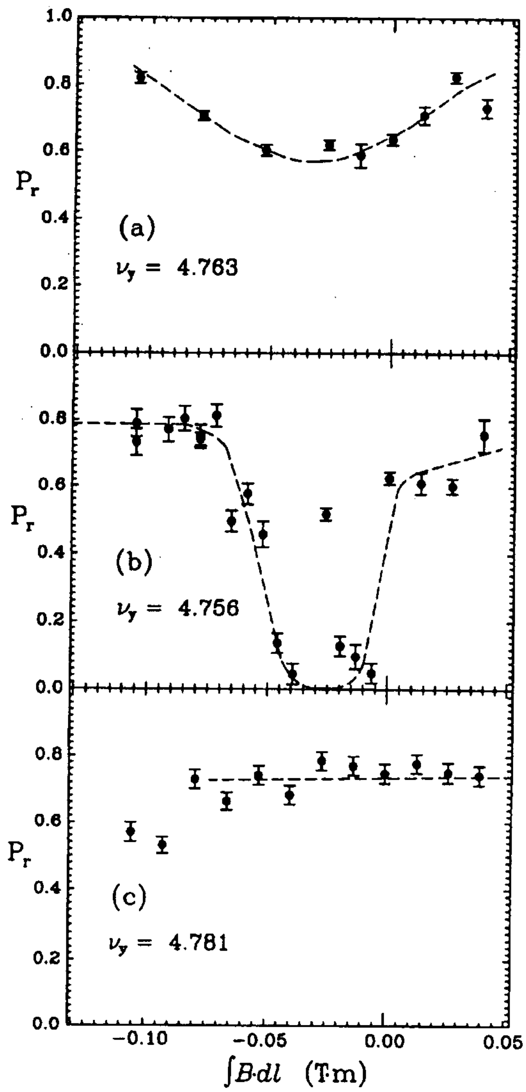


Fig. B15 Depolarization due to the second-order snake resonance occur when the vertical betatron tune is near a quarter-integer.[28]

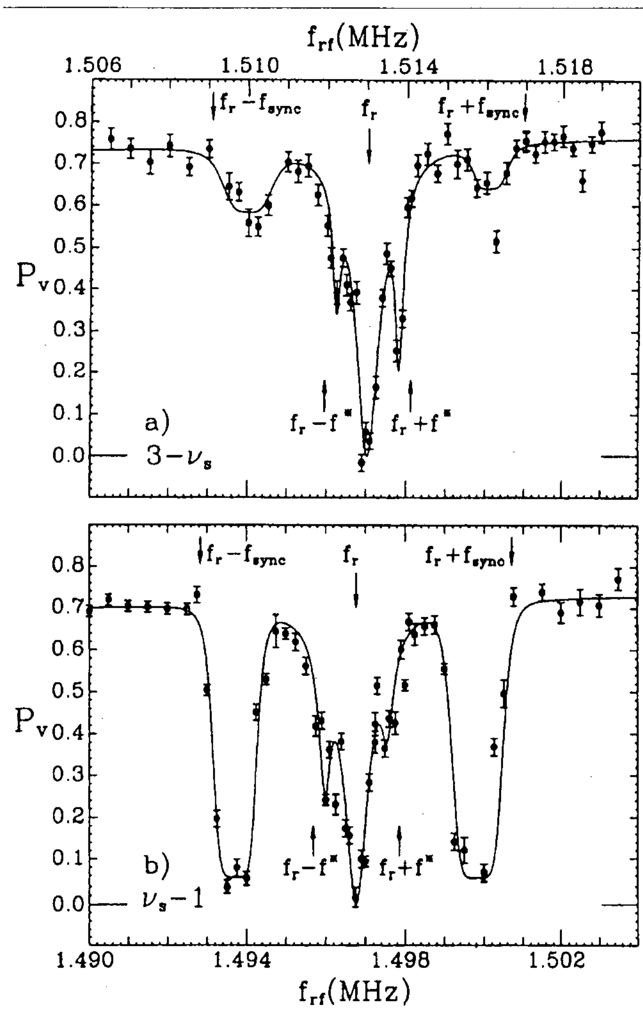


Fig. B16 The unexpectedly wide synchrotron sideband resonances near an rf depolarizing resonance.[33]

Experiment CE-69[200] was approved with high priority in June 1997 for 96 shifts. Our goals included: building an rf dipole; further studying overlapping depolarizing resonances; further studying both rf and intrinsic snake depolarizing resonances; and increasing the spin-flipping efficiency with a full snake. The results of these studies, which are discussed below, should be important to possible high-energy polarized proton beams at RHIC, UNK, HERA, Fermilab, and LHC.

In 1999, we created an rf-induced snake depolarizing resonance using an rf-solenoid magnet in the IUCF Cooler Ring containing a nearly 100% Siberian snake.[35] We found that the primary snake rf resonance also had two weaker synchrotron sidebands, shown in Fig. B17, which are second-order snake resonances. They were probably caused by the energy-dependent strength of the solenoid snake due to the Lorentz contraction of its longitudinal integral $\int B d\ell$. This is the first observation of an rf synchrotron-sideband snake depolarizing resonance in the presence of a nearly-full snake.

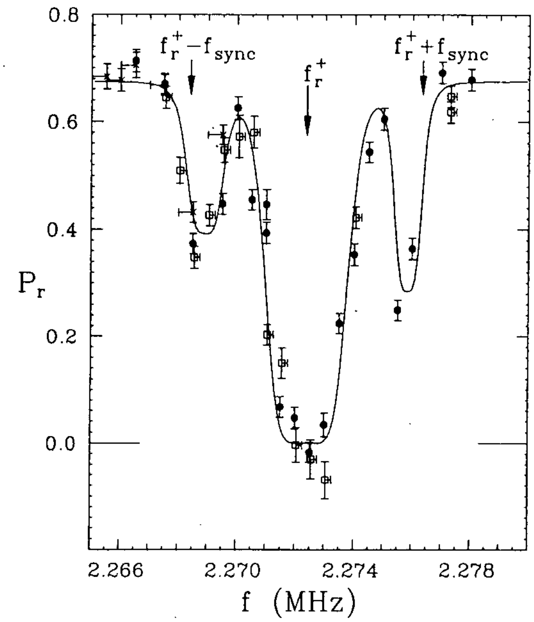


Fig. B17 Rf-induced snake depolarizing resonance.[35] The measured radial proton polarization at 104.1 MeV is plotted against the rf-solenoid's frequency. The fit uses a third-order Lorentzian for the primary resonance and two unequal second-order Lorentzians for the synchrotron sidebands.

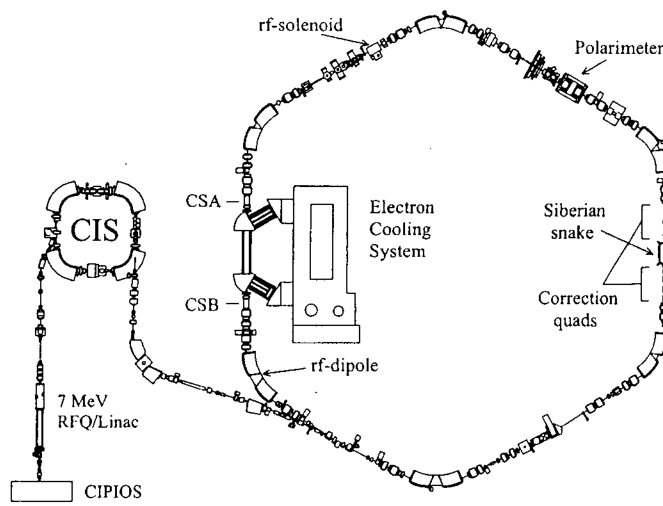


Fig. B18 The new IUCF layout including its new Cooler Injector Synchrotron (CIS) and its new CIPIOS polarized ion source. Also shown in the Cooler Ring are the rf-dipole, the rf-solenoid, the polarimeter, and the Siberian snake.

We demonstrated for the first time spin-flipping of a polarized proton beam stored in a ring containing a nearly 100% Siberian snake; we did this using a snake depolarizing resonance induced by an rf-solenoid magnet. Slowly crossing such an rf induced resonance by sweeping the rf magnet's frequency can flip the beam polarization. After optimizing the rf-solenoid's ramp time, frequency range, and voltage, we earlier reached a spin-flip efficiency of about 91±1%. This spin-flip efficiency was probably reduced because of synchrotron sidebands around the rf induced snake resonance. In a subsequent experiment, we tried to improve the spin-flip efficiency by eliminating possible synchrotron sidebands. Using multiple spin-flips, we then measured the maximum spin-flip efficiency to be $97 \pm 1\%$.[38,39]

In 1999, we used an rf-dipole to spin-flip a 202.7 MeV vertically polarized proton beam stored in the IUCF Cooler Ring with no Siberian snake.[40] This experiment was the first polarized run with its new Cooler Injector Synchrotron and its new CIPIOS polarized ion source, which is shown in Fig. B18.

We first set the vertical betatron tune ν_y to avoid the measured ν_y value of the $G\gamma = 7 - \nu_y$ intrinsic depolarizing resonance in the Cooler Ring. We then flipped the spin by ramping the frequency of an rf-dipole through an rf-induced depolarizing resonance.

After optimizing the rf-dipole's frequency ramp parameters, we used multiple spin-flips to measure a maximum spin-flip efficiency of 97.5±1%.[40] The multiple spin-flip data are shown in Fig. B19. Since a dipole's spin rotation is energy independent, a dipole, unlike a solenoid, is practical for spin-flipping polarized beams in high energy rings.

During April 2000, we used a partially upgraded rf-dipole to spin-flip a 120 MeV horizontally polarized proton beam in the presence of a nearly-full Siberian snake.[41] The results were very promising. As shown in Fig. B20, we reached a spin-flipping efficiency of 86.5±0.5% at the maximum rf voltage available with our rapidly constructed resonant LC circuit. With lower voltages on the rf-dipole, the spin-flip efficiency was much smaller; this indicates that an even higher rf voltage should further increase the spin-flip efficiency. This result strongly suggests that we should fabricate an rf-dipole to provide spin-flipping capability for the new MIT-Bates 1 GeV polarized electron storage ring. In July and November 2000, we increased the spin-flip efficiency with an rf dipole and a full Siberian snake to well above 90%; the final analysis is occurring now.

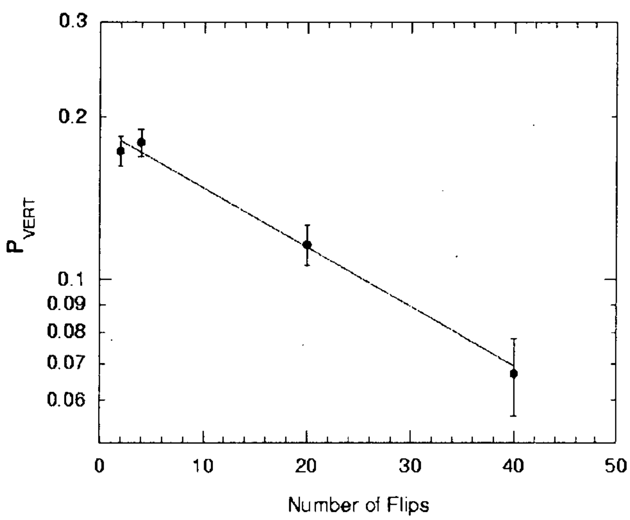


Fig. B19 The measured vertical proton polarization at 202.7 MeV is plotted against the number of spin-flips, n, with an rf-dipole and no Siberian snake. Fitting the data with $P_n = P_0 \cdot \eta^n$ gave a spin-flip efficiency η of 97.5 ± 1%.[40]

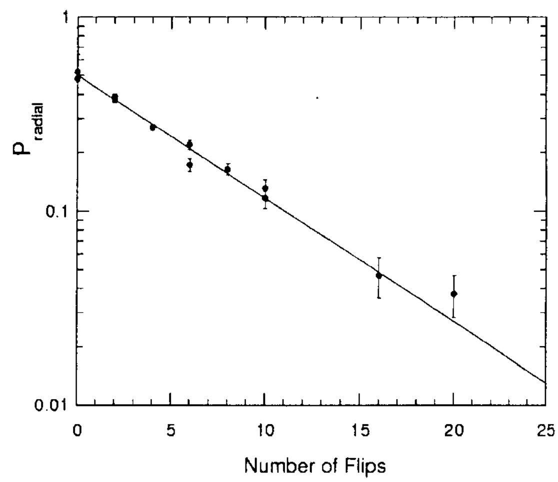


Fig. B20 The measured radial proton polarization at 120 MeV is plotted against the number of spin-flips with an rf-dipole and with a nearly-full Siberian snake. By fitting the data with $P_n = P_0 \cdot \eta^n$, we determined the spin-flip efficiency η to be about 86.5 ± 0.5%.[41]

In November 2000, we also confirmed, with much improved precision, the existence and behavior of the earlier discovered[28] second-order snake resonance $\nu_s = n \pm 2\nu_y$. We also found and studied another second-order snake resonance $\nu_s = n \pm 2\nu_x$. Moreover, we discovered and then studied yet another snake resonance, which may be the $\nu_s = n \pm 3\nu_y$ third order depolarizing resonance. If confirmed, this would be the first observation of a third order depolarizing resonance; such resonances are very weak at the IUCF Cooler Ring but may be a non-trivial problem at much higher energy rings such as RHIC and HERA.

B.4 Polarized Proton Acceleration at SSC

In 1990, the SPIN Collaboration, which is led by our Spin Physics Center, submitted EOI-001 to the SSC; [197a] we proposed to accelerate polarized protons to 20 TeV in each ring and then study spin effects in $\sqrt{s} = 40$ TeV proton-proton inclusive collisions. This EOI was partially approved, in that the SSC lattice was changed to include, in each 20 TeV ring, 26 empty straight sections each 20 meters long, for the *possible* later installation of 52 Siberian snakes. We then worked with the SSC staff on a detailed design of the hardware required to accelerate polarized protons through each ring of the SSC complex with no significant depolarization. Unfortunately, the SSC was cancelled before accelerating either polarized or unpolarized protons.

B.5 Polarized Proton Acceleration at Fermilab's Main Injector and Tevatron

Starting in September 1991, Fermilab provided Michigan with a total grant of $366,000 for the SPIN Collaboration to carefully study the possibility of accelerating polarized protons in Fermilab's LINAC, Booster, Main Injector and Tevatron. The resulting plan is shown in Fig. B21 and described in the Collaboration's detailed Reports on the *Acceleration of Polarized Protons in the Fermilab Main Injector and Tevatron*[102,108,109] which were submitted in 1992, 1994 and 1995. These Reports also discussed some possible high energy spin experiments. This polarization capability would allow studies of the one-spin dependence of $\overline{p} - p$ collisions at 2 TeV as well as fixed-target one-spin and two-spin experiments at 120 GeV.[23,24,64,65,68,73,74,78,79,82–85,87,88,93–95,129,132] In late 1995 Fermilab decided not to then proceed with this $25 Million program.

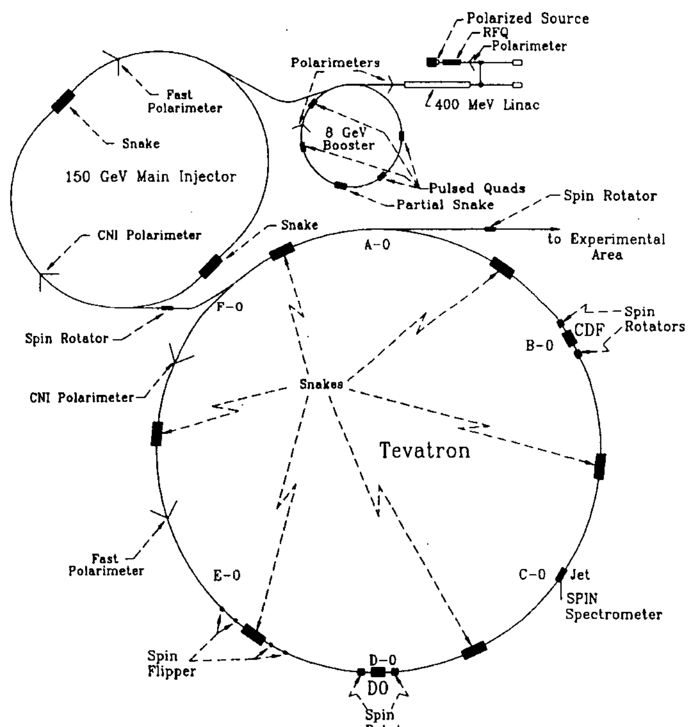


Fig. B21 Modifications to Fermilab's Main Injector and Tevatron for polarized proton acceleration.[109]

B.6 Polarized Proton Acceleration at DESY's HERA

The SPIN Collaboration, which is listed in Table B1, then began to study how to accelerate an 820 GeV polarized proton beam at HERA. In 1996, the DESY Directorate provided DM 100,000 to the SPIN Collaboration to study producing, accelerating, and storing polarized protons at the HERA accelerator complex. The 90-page Polarized HERA Report[110], which was based on the much longer 1995 Fermilab Report[109], was submitted on 8 November 1996. This 1996 Report identified two significant issues for further study:

1. increasing the intensity of the proposed HERA polarized proton beam;
2. improving the spin stability of a polarized proton beam in the 4-fold-symmetric HERA ring.

In February 1997, the DESY Directorate provided DM200,000 to the SPIN Collaboration for further R&D on these two issues. Much of this sum went for polarized ion source R&D at TRIUMF, which recently achieved a polarized H^- intensity of about 5 mA. HERA's planned luminosity upgrade may reduce its emittance and rms orbit distortions enough to weaken all its depolarizing resonances to strengths below perhaps $\varepsilon = 0.8$; then the four snakes proposed in the 1996 Report might be adequate. Otherwise, recent R&D studies suggest that 8 snakes in HERA should work, but would require significant changes to the accelerator lattice, as shown in Fig. B22. Bending Siberian snakes and Type-3 snakes have also been proposed recently for the HERA ring. A large workshop on Polarized Protons at High Energies at DESY occurred in May 1999. On 25 June 1999, we submitted our Update Report *Acceleration of Polarized Protons to 920 GeV at HERA*;[115] this should complete our program at HERA until perhaps 2002, when the DESY Directors plan to decide upon accelerating polarized protons in HERA. We have had discussions about possibly bringing our Mark-II jet target to HERA to study spin effects in p–p scattering at 920 GeV.

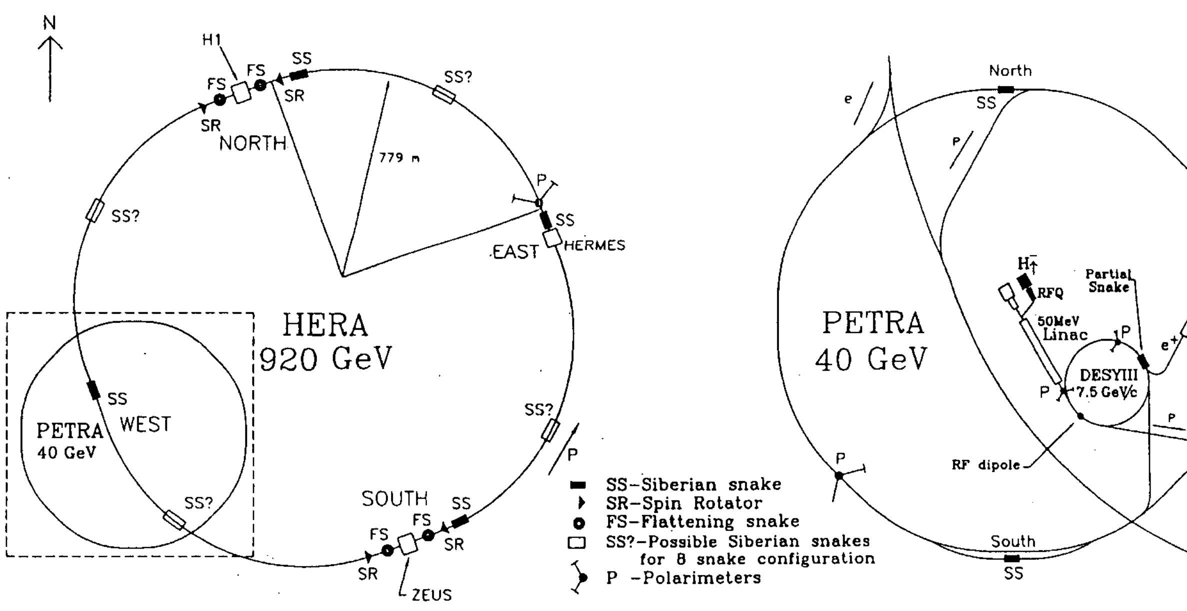


Fig. B22 Preliminary design of polarized proton hardware for HERA.[115]

Table B1. SPIN@HERA Collaboration

23 June 1999

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B.7 NEPTUN-A: High-$P_\perp^2$ p-p Elastic A_n at 400 GeV UNK

The NEPTUN-A Agreement was signed in March 1989 by the University of Michigan and IHEP-Protvino to study spin effects in violent proton-proton collisions at the then-planned 0.5 to 3 TeV UNK facility in Protvino, Russia.[72] Since then, NEPTUN-A has been a significant part of the annual US-Russian JCC Agreement. During the 1990's, we developed our laboratories in Ann Arbor as the staging area for NEPTUN-A. We have made good progress on the Michigan Polarized Jet, as described in Section **B.8**. We are also building and testing detectors for our 50-m-long spectrometer,[146] which is shown in Fig. B23. A joint NEPTUN and NEPTUN-A Collaboration Meeting is typically held in Protvino, Russia each September and in Ann Arbor each May. The NEPTUN-A Collaboration presently contains about 25 Americans and 25 Russians.

The NEPTUN-A experiment plans to study spin effects in violent proton-proton collisions, as the first experiment at the new 21 km circumference 400 GeV UNK-1 accelerator at IHEP-Protvino in Russia. Although the huge 60 m x 15 m SS-3 underground hall and the 55-m-long NEPTUN-A cave for our experiment are finished, Russia's economic situation in 1998 has placed UNK and NEPTUN-A on long-term standby status. MINATOM is supporting 100 workers to maintain the huge complex.

Because of UNK's recent standby status, the NEPTUN/NEPTUN-A Collaboration decided in September 1998 to move much of the NEPTUN equipment to U-70 for use in RAMPEX.[198]

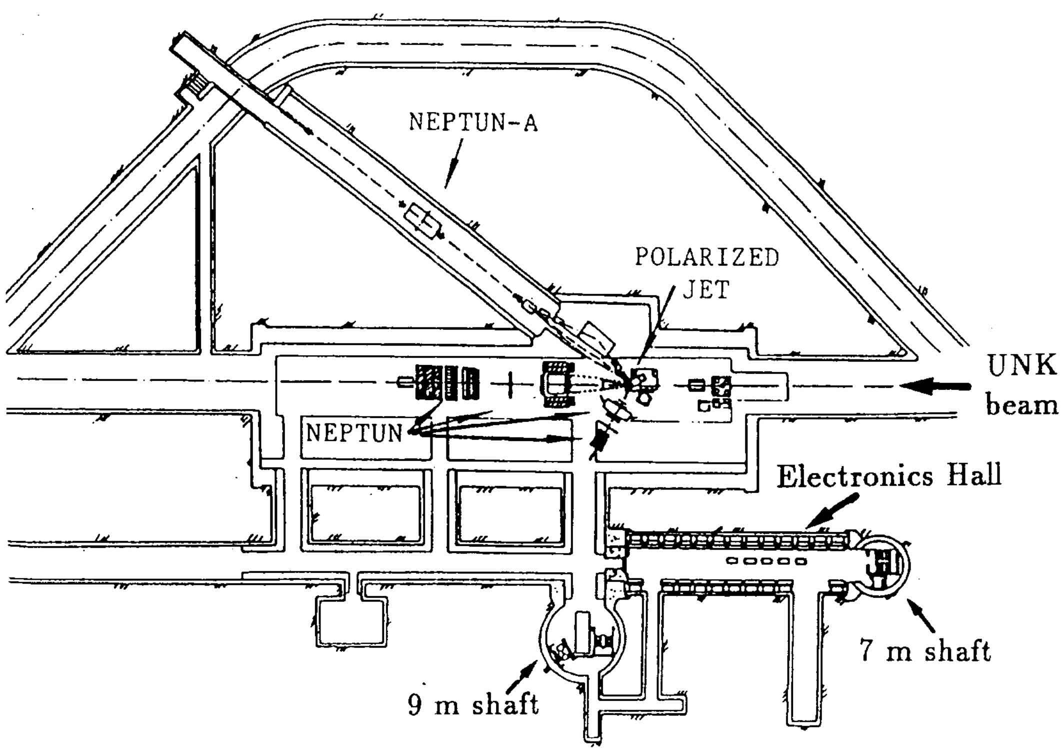

Fig. B23 The NEPTUN-A spectrometer[72] with the 400 GeV UNK beam passing through the Michigan Polarized Jet.[69]

B.8 Michigan Ultra-Cold Spin-Polarized Proton Jet

With the help of D. Kleppner of MIT and G.R. Court of Liverpool, we built the Prototype Ultra-cold Spin-polarized Atomic-hydrogen Jet, which uses a very high magnetic field and a very low temperature to separate hydrogen atoms according to their electron spin state; an rf transition unit then changes the electron-spin-polarized monoenergetic atomic beam into a proton-spin-polarized beam. We then used the Prototype Jet to successfully demonstrate the world's first microwave extraction of spin-polarized hydrogen atoms.[8,117] A 2 watt at 213 GHz microwave tube, purchased from Varian, was used for these microwave extraction studies with a 7.6 T superconducting magnet. Then we developed and successfully tested a no-microwave method of extraction and obtained similar intensities.[17,122,125,128,133,134] We are now using no-microwave extraction both because of its operational simplicity and to reduce high-technology export problems to UNK in Russia.

To improve the intensity and optics of the Michigan (Mark II) Jet for NEPTUN-A, we tried to better focus the spin-polarized atomic hydrogen beam emerging from the Prototype Jet's 20-mW-at-0.3-K dilution refrigerator. Thus, we developed an approximately quasi-parabolic focusing mirror machined of copper and then highly polished and coated with "hydrogen-reflecting" superfluid helium-4, as shown in Fig. B24. This highly polished mirror increased the Prototype Jet's hydrogen intensity by a factor of about 7.5, giving about 3.5 10^{15} hydrogen atoms per sec into a compression tube detector.[16] This success convinced us to change the Mark II design to include a superfluid-helium-coated focusing mirror, which reduced the bore of the downstream superconducting sextupole to 11 cm.

After completing these Prototype Jet studies, we designed and fabricated all major parts of the 5-meter-high Michigan (Mark II) Ultra-cold Spin-polarized Atomic-hydrogen Jet target, [69,70,89,136–138,141,149–153,156–158,161–163,166–169,174,175,177,180–182,187,189,194,196] which is shown in Fig. B25. These now-fabricated components include:

1. the 100 mW at 0.3 K dilution refrigerator,
2. the 12 T superconducting solenoid,
3. the superconducting sextupole,
4. the huge 1.2 10^7 liter s^{-1} "catcher" cryopump,[29,89,166]
5. the four large cylindrical vacuum chamber modules,
6. their liquid Helium and liquid Nitrogen tanks,
7. two high quality TMP 1000 Leybold turbopumps from SSC surplus.

We have now tested all of these state-of-the-art cryogenic components. After some R&D, all these components met or exceeded the design specifications, except the dilution refrigerator, whose cooling power is about 75 mW at 0.3 K compared to its design value of 100 mW. The current Jet R&D requires no major new hardware, but it does require much detailed and delicate work in the very small but complex dilution refrigerator and the new atomic beam transport line which brings the hydrogen atoms from the 300 K dissociator down into the 0.3 K mixing chamber of the dilution refrigerator. Because the Michigan Jet is so large, each cool-down requires about 5 days of 24-hour operation; the warm-up requires another day. So far the data from each cool-down has pointed to some required improvements such as: eliminating conductive, convective, or radiative heat leaks; improving thermal contacts; or eliminating superfluid helium flow paths. Designing and implementing these improvements usually requires two weeks. Thus, we have typically had one cooldown per month since we started testing, in September 1997, the almost-complete Jet, which is shown in Fig. B25. The final liquid nitrogen tank below the mixing chamber was fabricated and installed. Its earlier absence increased the lower nitrogen shield's temperature from 80 K to about 200 K; despite the small solid angle, the shield's T^4 radiation heat load to the mixing chamber was apparently significant.

We used "electroforming" to fabricate an exactly parabolic mirror, similar to the Prototype Jet's mirror, which is coated with superfluid helium-4. We designed and tested a Prototype warm rf transition unit to transfer the Michigan Jet's electron-polarisation into proton-polarization; its measured polarization transfer efficiency was 95-97%.[142,152,167,175,177] We are now testing a cold Prototype rf unit.[182] In collaboration with D. Kleppner of MIT, we designed, fabricated and tested a hydrogen Maser polarimeter, which measured the polarization of a test beam to a 2% precision.[143,153,157,161]

In October 1998, the Michigan Jet produced its first electron-spin-polarized atomic beam. By July 2000, we reached a measured cooling power of over 70 mW at 300 mK and an electron-spin-polarized atomic hydrogen beam intensity of about $2.8 \cdot 10^{15}$ H s^{-1} into a 0.3 cm^2 area;[187,189] the beam's proton-spin-polarization was about 50%. These results are shown in Figs. B26 and C6.

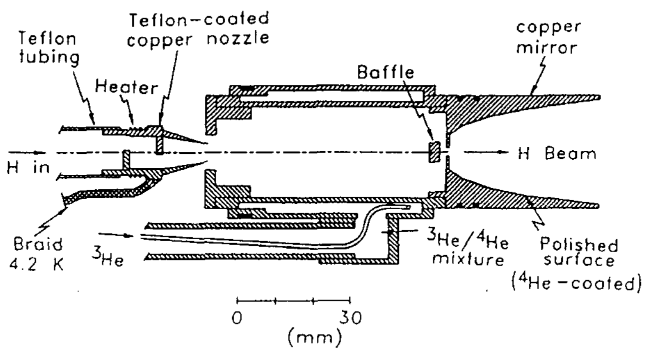

Fig. B24 Superfluid-helium-coated quasi-parabolic focusing mirror in the 0.3 K Prototype Jet.[16]

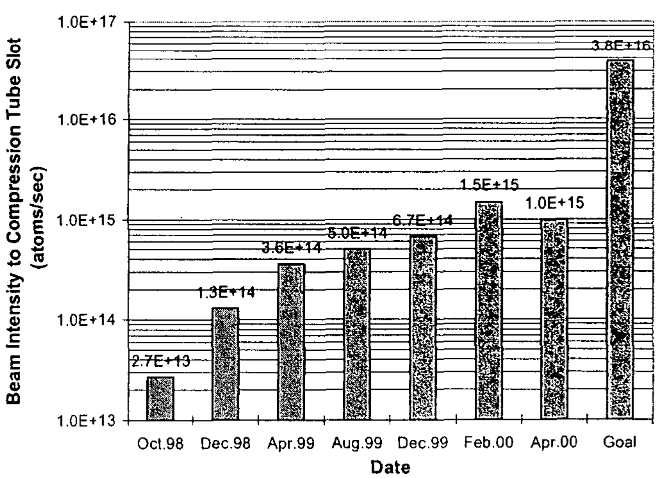

Fig. B26 Michigan Jet Intensity vs. Run Date.[187,189]

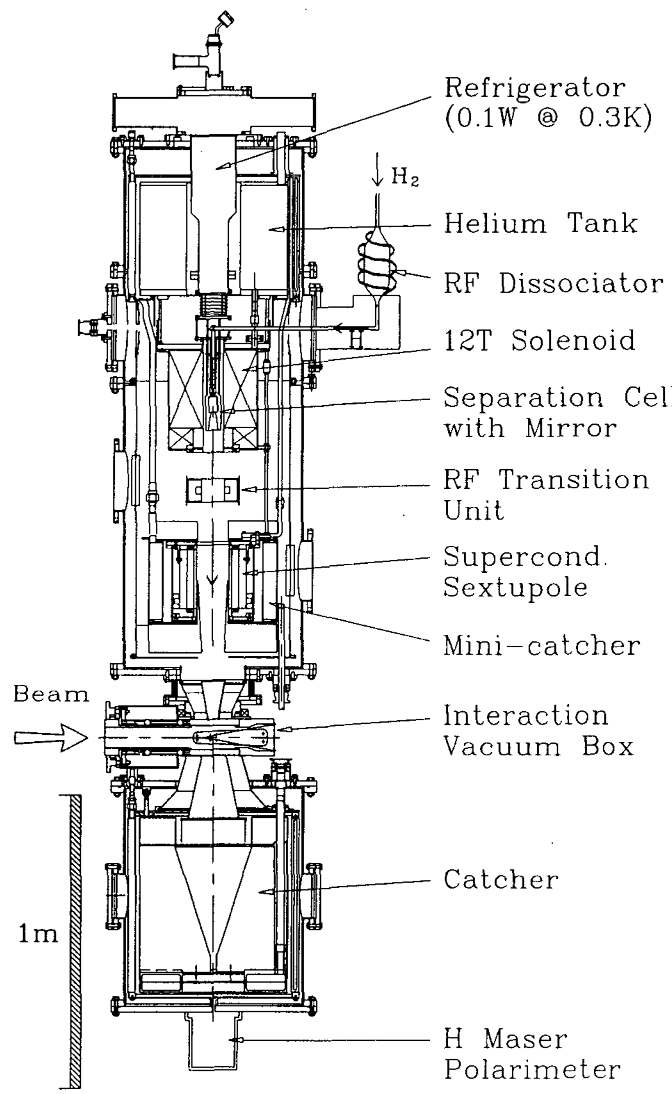

Fig. B25 Michigan Ultra-cold Spin-polarized Atomic-hydrogen Jet.[122]

B.9 SPIN@RHIC at Brookhaven

On 17 September 1997, after strong encouragement by the Brookhaven Directors and staff, we submitted the SPIN@RHIC Letter of Intent;[201] this experiment proposed to:

1. Calibrate the RHIC 250 GeV proton beam polarization by using our Michigan Polarized Jet to measure A_n in p-p elastic collisions in the CNI region.
2. Use the Jet to measure A_n and A_{nn} in large-$P_\perp^2$ p-p elastic scattering.
3. Use the Jet to measure A_n and A_{nn} inclusive scattering in a fairly wide X_F and $P_\perp$ range.

On 30 Sept 97, after consulting with our IHEP Collaborators and the IHEP Directors, we e-mailed Brookhaven that this Letter of Intent could be considered as a formal Proposal, so that it could be considered at the 23-24 Oct 97 Brookhaven PAC Meeting, as Brookhaven had requested. On 31 Oct 97, Brookhaven informed us that the SPIN@RHIC Proposal was rejected. Then, in a 17 Nov 97 e-mail, T. Kirk suggested that we join the BRAHMS Collaboration to help them to measure A_n and A_{nn} in 250-250 GeV proton-proton collisions.

With the expected operation of RHIC as a polarized proton collider at $s^{1/2} = 500$ GeV, and our past involvement with the AGS polarized beam, we are certainly interested in this program. Thus, we submitted in February 2000 an Update Proposal[202] to bring the Michigan Ultra-cold Jet to RHIC, where it could simultaneously be the target for:

- an absolute CNI elastic polarimeter[202] for RHIC,
- A_n and A_{nn} measurements in 250 GeV p-p inclusive scattering at large $P_\perp^2$ and in CNI elastic scattering.[202]

In April 2000, Brookhaven again rejected our Proposal and indicated that they do not expect to further consider our Jet Target for RHIC.

B.10 SPIN@FERMI at Fermilab

In August 1998, we again proposed to Fermilab[203] to use our solid polarized proton target to do a large-$P_\perp^2$ p-p elastic A_n experiment at 120 GeV at $P_\perp^2$ = 1-12 (GeV/c)^2 in the M-West area with Fermilab's new Main Injector. The proposed layout of the experiment is shown in Fig. B27. We presented our proposal (P-910) at the May 1999 Fermilab PAC Meeting devoted to 120 GeV fixed target experiments. We also explored with Fermilab the following possible projects:

- Measure A_n and A_{nn} in 3 TeV elastic and inclusive p-p collisions with the Mark II Jet at Fermilab's suggested 3 TeV Booster.
- Help accelerate 150 GeV polarized protons in the Main Injector and then in the possible 3 TeV Booster for the suggested 50 TeV x 50 TeV VLHC.

On 6 July 1999, Fermilab rejected this proposed fixed-target experiment.

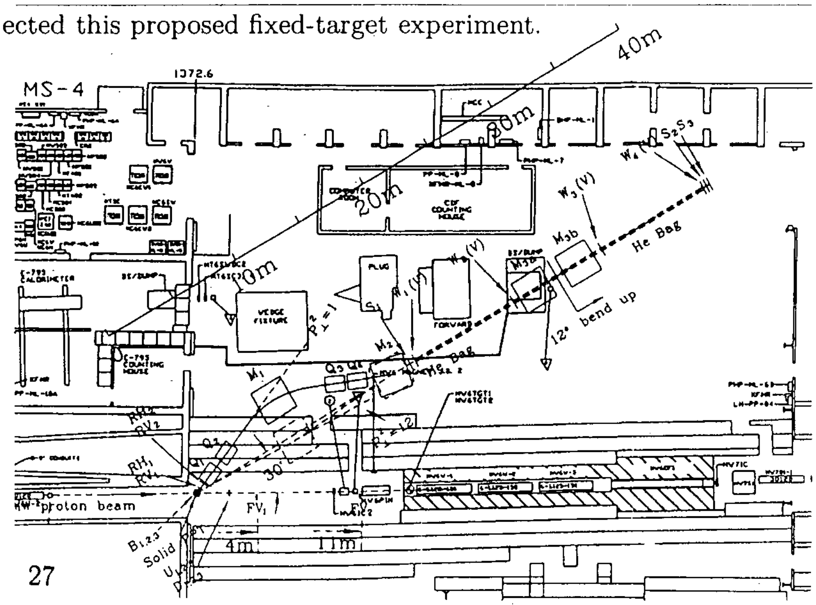

Fig. B27 Proposed Fermilab large-$P_\perp^2$ p-p elastic experiment in the Meson Hall's MW beamline.[203]

B.11 PROZA and RAMPEX at U-70

During 1991 to 1997, we participated in several runs of the recently ended PROZA experiment at U-70 in IHEP-Protvino, Russia. PROZA was replaced by the Russian AMerican Polarization Experiment (RAMPEX), which is shown in Fig. B28. In addition to providing some physics data,[135,185] PROZA and RAMPEX have been providing valuable experience in running at a Russian accelerator.

RAMPEX is a collaboration between IHEP-Protvino, JINR-Dubna, INP-Gatchina and Michigan.[198] Using the spectrometer shown in Fig. B28, RAMPEX is studying one-spin asymmetries in $p-p$ and $\pi-p$ interactions at 70 and 40 GeV using IHEP's 70 GeV U-70 accelerator. There were U-70 runs in November-December 1996 and March-April 1997, which allowed successful tests of the RAMPEX detectors. The 3-week-long first data run of RAMPEX using the JINR-Dubna frozen-spin solid polarized proton target occurred in April 1999; three Michigan physicists participated in this successful run. Another data run, this time 6 weeks long, occurred in March-April 2000; three Michigan physicists participated in this most recent and successful run.[185] The 40 million raw events on the A_n spin asymmetry in inclusive π^0 production in 40 GeV $\pi^- - p_\uparrow$ collisions are now being analyzed. The most recent RAMPEX run occurred during November-December 2000, and was quite successful.

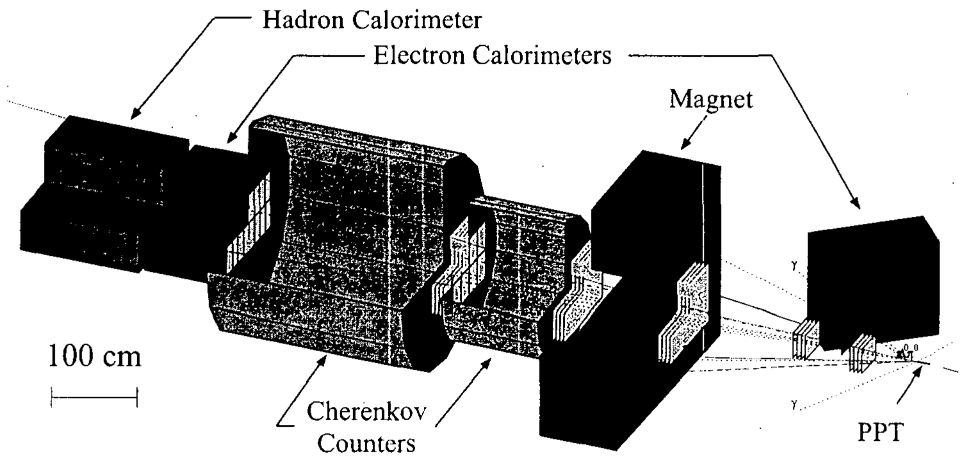

Fig. B28 RAMPEX experiment at U-70.[198]

B.12 Spin and Accelerator Theory in the Spin Physics Center

Ya.S. Derbenev, the senior co-inventor of the Siberian snake, has spent most of the past 10 years in Michigan. During these 10 years, he has been a magnet for creative accelerator theory in both polarized beam and electron cooling; his productivity has been quite impressive.[11,41–45,47,126,190–193,196,207–213,215,218–220,223–225,227–235] However, we have not had full support for him since his Visiting Professorship ended in September 1993. In 1998, he accepted a half-time position as a Senior Research Scientist and Adjunct Professor. Two other distinguished accelerator theorists, E.D. Courant and A.W. Chao, usually spend one to four weeks with us each year.

We also host extended visits each year by distinguished High Energy Spin Theorists, including S.M. Troshin and ex-IHEP-Director L.D. Soloviev, which have resulted in significant publications[31,48a,171]; these visits are often paid for by the Russian Ministry of Science. There are many shorter visits by active Spin Physics theorists; our weekly High Energy Spin Physics Seminar is sometimes the first forum for new Spin Physics results, both experimental and theoretical.

B.13 Conferences, Symposia and Workshops

We help to organize and sponsor various International Symposia, Conferences, and Workshops on High Energy Spin Physics; on the overlap of High Energy and Nuclear Physics; and on High Energy Elastic Scattering. Some examples during 1989-2001 are:

Kent M. Terwilliger Memorial Symposium, Ann Arbor, October 1989
Workshop on Polarized Ion Sources and Jets, KEK, JAPAN, February 1990
9^{th} Int'l High Energy Spin Physics Symposium, Bonn, GERMANY, September 1990
Workshop on Polarized Colliders, Penn State, November 1990
4^{th} Intersections of Particle and Nuclear Physics Conference, Tucson, May 1991
4^{th} Spin Workshop, Protvino, Russia, September 1991
Workshop on Polarized Gas Targets, Heidelberg, GERMANY, September 1991
10^{th} Int'l High Energy Spin Physics Symposium, Nagoya, JAPAN, November 1992
Polarized Gas Targets Workshop, Madison, Wisconsin, May 1993
5^{th} "Blois" High Energy Elastic Scattering Workshop, Brown University, June 1993
5^{th} Spin Workshop, Protvino, RUSSIA, September 1993
11^{th} Int'l High Energy Spin Physics Symposium, Indiana University, September 1994
5^{th} Intersections of Particle and Nuclear Physics Conference, St. Petersburg, Florida, June 1994
6^{th} "Blois" Conference on Elastic and Diffractive Scattering, Blois, FRANCE, June 1995
5^{th} Polarized Ion Source and Target Workshop, Cologne, GERMANY, June 1995
SPIN 95 Workshop, Protvino, RUSSIA, September 1995
8^{th} Polarized Solid Target Workshop, TRIUMF, CANADA, June 1996
12^{th} Int'l High Energy Spin Physics Symposium, Amsterdam, NETHERLANDS, September 1996
6^{th} Intersections of Particle and Nuclear Physics Conference, Big Sky, Montana, June 1997
7^{th} "Blois" Conference on Recent Advances in Hadron Physics, Seoul, KOREA, June 1997
SPIN 97 Workshop, JINR, Dubna, RUSSIA, September 1997
7^{th} Int'l Workshop on Polarized Gas Targets, Univ. of Illinois, Urbana, August 1997
Int'l Workshop on NMR for Polarized Targets, Charlottesville, Virginia, April 1998
Workshop on Spin at Low Energy, St. Petersburg, RUSSIA, September 1998
13^{th} Int'l Symposium on High Energy Spin Physics, Protvino, RUSSIA, Sept. 1998
Workshop on Intermediate Energy Spin Physics, Julich, GERMANY, Nov. 1998
8^{th} "Blois" Conference on Hadron Physics, Protvino, RUSSIA, July 1999
SPIN 99 Workshop, Prague, CZECH REPUBLIC, Sept. 1999
Int'l Workshop on Polarized Sources and Targets, Erlangen, GERMANY, Sept.-Oct. 1999
7^{th} Intersections of Particle and Nuclear Physics Conference, Quebec City, CANADA, June 2000
Int'l Workshop on Polarized Electron Sources, Nagoya, JAPAN, Oct. 2000
14^{th} Int'l Spin Physics Symposium, Osaka, JAPAN, Oct. 2000
9^{th} "Blois" Conference on Hadron Physics, Prague, CZECH REPUBLIC, July 2001
15^{th} Int'l Spin Physics Symposium, Brookhaven, Sept.-Oct. 2002.

B.14 Training Students and Postdoctoral Fellows at Spin Physics Center

We train about 10 undergraduates in our Laboratory each year. Our mixture of high energy detectors, superconducting magnets, sub-Kelvin cryostats, and Siberian snake hardware seems to provide good training for young physics and engineering students. It is hard to keep track of the some-200 undergraduates who have passed through our Laboratory, but some are now quite successful. Each year we typically train one or two undergrads from other colleges and universities using funds from Michigan's NSF-sponsored REU program.

As shown below, since 1990, there have been nine American Ph.D.'s, including seven from Michigan, and two from Indiana who joined our Siberian snake experiments. Each year since FY1991, we have hosted one or two Accelerator Physics Diploma Thesis students from Moscow State University, as listed below. They write their Diploma Thesis based on research typically in our IUCF Siberian snake experiments or our TeV polarized proton beam design studies.

Also listed on the next page are 41 Postdoctoral Research Fellows who worked with us.

B.14.a Thesis Students

	Name	Year	Current Position
1.	S.W. Kormanyos	1966	Senior Fellow, Boeing, Seattle
2.	A.M.T. Lin	1968	Associate Research Scientist, Univ. of Michigan
3.	J.L. Day	1969	Faculty, Hannaman Medical College, Philadelphia (Deceased)
4.	M.L. Marshak	1970	Professor & Past Academic Vice-President, Univ. of Minnesota
5.	B.A. Babcock	1972	Staff Physicist, Williams College
6.	H.E. Mietinen	1975	Professor, Rice University
7.	T. Shima	1981	Lecturer, Kyoto Academy of International Culture, JAPAN
8.	M.E. Hejazifar	1983	Chair & Associate Professor, Wilmington College, Ohio
9.	F.Z. Khiari	1986	Assistant Scientist, King Fahd Univ., SAUDI ARABIA
10.	N. Merminga	1989	Staff Physicist, Jefferson Lab
11.	I. Gialas	1990	Assistant Professor, University of Crete, GREECE
12.	J.E. Goodwin†	1990	was Postdoctoral Fellow, Fermilab
13.	M.G. Minty†	1991	Staff Physicist, DESY, GERMANY
14.	J.A. Stewart	1991	Senior Staff Physicist, DESY-Zeuthen, GERMANY
15.	V.A. Anferov*	1992	Senior Research Associate, IUCF
16.	D.S. Shoumkin*	1993	Research Fellow, IHEP-Protvino, RUSSIA
17.	A.V. Koulsha*	1994	Electronics Industry, Moscow, RUSSIA
18.	C-M. Chu	1994	Staff Physicist, Jefferson Lab
19.	B.S. van Guilder	1994	Faculty, New Jersey State College, Montclair
20.	B.B. Blinov*‡	1995	Postdoctoral Research Fellow, Univ. of Michigan
21.	D.A. Crandell	1996	Staff, Creative Solutions, Dexter, Michigan
22.	L.V. Alexeva*	1996	Research Fellow, IHEP-Protvino, RUSSIA
23.	S.M. Varzar*	1996	Research Fellow, IHEP-Protvino, RUSSIA
24.	S.V. Koutin*	1997	High Tech Industry, Moscow, RUSSIA
25.	M.A. Bychkov*	1998	Ph.D. Student in Physics, Univ. of Virginia
26.	K.V. Sourkont*	1999	Doctorate Student in Physics, Moscow State Univ., RUSSIA
27.	D.Yu. Kantsyrev*	2000	Ph.D. Student in Economics, Univ. of Southern California
28.	B.B. Blinov	2000	Postdoctoral Research Fellow, Univ. of Michigan
29.	S.E. Gladycheva	2000	Music School, Univ. of Michigan
30.	V.S. Morozov*	2001	Visiting Research Investigator, Univ. of Michigan
31.	M.A. Leonova*	2002?	

† Ph.D. at Indiana University (Not paid by Michigan)

* Diploma Degree at Moscow State University (In collaboration with Prof. Yu. M. Ado)

‡ Later received Ph.D. at Michigan (See No. 28)

B.14.b Postdoctoral Research Fellows

	Name	Year	Current Position
1.	K. Ruddick	1964-66	Professor, University of Minnesota
2.	J.R. O'Fallon	1965-66	Director, Division of High Energy Physics, U.S. Dept. of Energy
3.	C.W. Akerlof	1966-68	Professor, University of Michigan
4.	D.G. Crabb	1967-69	Research Professor, University of Virginia
5.	J.G. Asbury*	1968	Deputy Director Emeritus, Argonne National Laboratory
6.	J.K. Randolph	1968-70	Faculty, Williams College
7.	P. Schmuser	1968-70	Professor, University of Hamburg, GERMANY
8.	R.J. Ellis*	1970-71	was Staff Physicist, Los Alamos
9.	J.B. Roberts	1970-75	Professor, Rice University
10.	S.W. Gray	1972-74	Staff Physicist, Cornell University
11.	B.C. Brown	1973-74	Staff Physicist, Fermilab
12.	R.C. Fernow	1974-78	Physicist, Brookhaven National Lab
13.	W. de Boer	1974-76	Professor, University of Karlsruhe, GERMANY
14.	T.A. Mulera	1975-77	Senior Research Associate, Berkeley
15.	K. Abe	1976-78	Professor, KEK, JAPAN
16.	B. Sandler	1977-79	Staff Physicist, General Electric, Milwaukee
17.	A.J. Salthouse	1977-79	Senior Physicist, Bell Labs
18.	P.H. Hansen	1978-81	Associate Professor, Niels Bohr Institute, DENMARK
19.	P. Kyberd	1979	was Research Associate, Imperial College, ENGLAND
20.	M.J. Fujisaki	1979-81	Sony Electronics, Tokyo, JAPAN
21.	S.L. Linn	1979-82	Associate Research Scientist, Florida State University
22.	P.R. Cameron	1980-86	Research Engineer, Brookhaven National Lab
23.	R.S. Raymond	1982-85	Assistant Research Scientist, University of Michigan
24.	T. Roser	1984-86	Director, AGS and RHIC Division, Brookhaven National Lab
25.	R.A. Phelps	1986-88	Staff Scientist, IBM
26.	S.R. Mane	1987	Financial Analyst, Wall Street
27.	B. Vuaridel	1988-91	Associate Professor, University of Geneva, SWITZERLAND
28.	W.A. Kaufman	1988-91	Technical Staff, AT&T
29.	R. Baiod	1990-92	Staff, Chase Manhattan Bank
30.	E. Tjukanov	1991	Assistant Scientist, University of Turku, FINLAND
31.	V.G. Luppov	1991-92	Associate Research Scientist, University of Michigan
32.	J.A. Stewart	1991-94	Senior Staff Physicist, DESY-Zeuthen, GERMANY
33.	J. Duryea	1992-93	Assistant Professor, University of California Medical School
34.	J.S. Price	1993-94	Staff Scientist, General Electric, Milwaukee
35.	D.D. Caussyn	1994-95	Assistant Research Scientist, Florida State University
36.	C.M. Chu	1994	Staff Physicist, Jefferson Lab
37.	T.J. Liu	1995-96	Research Associate, University of California, Irvine
38.	V.A. Anferov	1995-00	Senior Research Associate, IUCF, Bloomington
39.	T. Kageya	1997-	Research Fellow, University of Michigan
40.	K. Yonehara	2000-	Research Fellow, University of Michigan
41.	B.B. Blinov	2000-	Research Fellow, University of Michigan

*Not paid by Michigan

C FUTURE PLANS OF THE SPIN PHYSICS CENTER

In November 1998, with the support of DoE, we became the Spin Physics Center with established world-class expertise and resources in:

- polarized scattering experiments [Sec. **B.1, B.7, B.9, B.10, B.11, C.1**],
- polarized proton, electron, and deuteron beam studies [Sec. **B.3, B.4, B.5, B.6, C.2, C.4**],
- Siberian snake experiments [Sec. **B.3, C.3**],
- solid and jet polarized proton targets [Sec. **B.6, B.9**],
- polarization and accelerator theory [Sec. **B.12**],
- spin meetings and training students [Sec. **B.13, B.14**].

Our future plans for the FY2001-2005 include the following:

1. SPIN@U-70: Very-large-$P_\perp^2$ elastic $p-p$ spin experiment at U-70,
2. Spin manipulation of polarized proton and deuteron beams at IUCF,
3. Further improving the Michigan Ultra-cold Polarized Proton Jet target,
4. Spin-flipper for polarized electron beam at MIT-Bates,
5. RAMPEX experiment at U-70,
6. HERMES experiment at DESY.

We are also considering possible future projects including:

7. Resuming NEPTUN-A experiment at UNK, (if UNK operates)
8. Polarized inclusive experiment at HERA,[110,115]
9. Work on Fermilab's proposed 3 TeV Booster for its proposed 50 TeV - 50 TeV VLHC,
10. Work on proposed EIC (MIT-Bates, Brookhaven and IUCF),
11. Move Siberian snake experiments to either MIT-Bates or COSY.

C.1 SPIN@U-70: Very-Large-$P_\perp^2$ elastic $p-p$ scattering at U-70

In May 1996, we were invited by the IHEP Directors to bring our solid Polarized Proton Target (PPT) to the IHEP-Protvino's 70 GeV proton accelerator, U-70, under the following arrangement:

- We would study $p-p$ elastic scattering at 70 GeV out to $P_\perp^2$ of about 10 (GeV/c)^2 using an unpolarized proton beam of 10^{12} per 10 second cycle; the luminosity would be about $2{\cdot}10^{34}$.
- IHEP identified an unoccupied "Channel 8" beamline position for this experiment; in December 1995, it appeared suitable for both the polarized target and the recoil spectrometer.
- IHEP would arrange to guarantee at least two runs of 45 days each year.
- Michigan and IHEP would sign a 5-year Agreement for this experiment.
- IHEP would formally agree that Michigan is free to use its ultra-cold spin-polarized jet target at another facility, such as HERA, until UNK is ready for the NEPTUN-A experiment.

In December 1996, we submitted the SPIN@U-70 proposal[199] to IHEP to study A_n in very-large-$P_\perp^2$ p–p elastic scattering at 70 GeV using the Michigan solid NH_3 target at U-70. Because of: the $2 \cdot 10^{34}$ luminosity with U-70's extracted proton beam; the 90% polarization of the Michigan solid PPT; and the NEPTUN-A spectrometer's large solid angle, we could measure A_n precisely out to $P_\perp^2 = 12$ (GeV/c)^2. This would considerably exceed the world's record of 7 (GeV/c)^2 from our 1990 AGS experiment.

IHEP found an excellent location for this experiment in the U-70 Channel 8 extracted proton beam (see Fig. C1) and has a detailed plan for installing the NEPTUN-A spectrometer at this site. However, a draft Agreement from IHEP, which was to guarantee 3 months of running each year, arrived with some unexpected problems and further discussion of SPIN@U-70, scheduled for 1997, was postponed. The SPIN@U-70 Collaboration is listed in Table C1.

Part of the delay at that time was due to insufficient electric power supply for U-70. Recently, electricity for U-70 seems available from a MINATOM nuclear power station in the Kaluga Oblast; indeed, there were successful RAMPEX data runs in 1999 and 2000 (See Section **B.8**). This seems to resolve the largest problem for SPIN@U-70. Since Fermilab rejected our similar SPIN@FERMI proposal[203] at its new 120 GeV Main Injector, we now give SPIN@U-70 our highest priority for the next five years. We now seek help from DoE and University of Michigan to find a way to successfully carry out this fundamental study of very-large-$P_\perp^2$ spin effects at IHEP-Protvino.

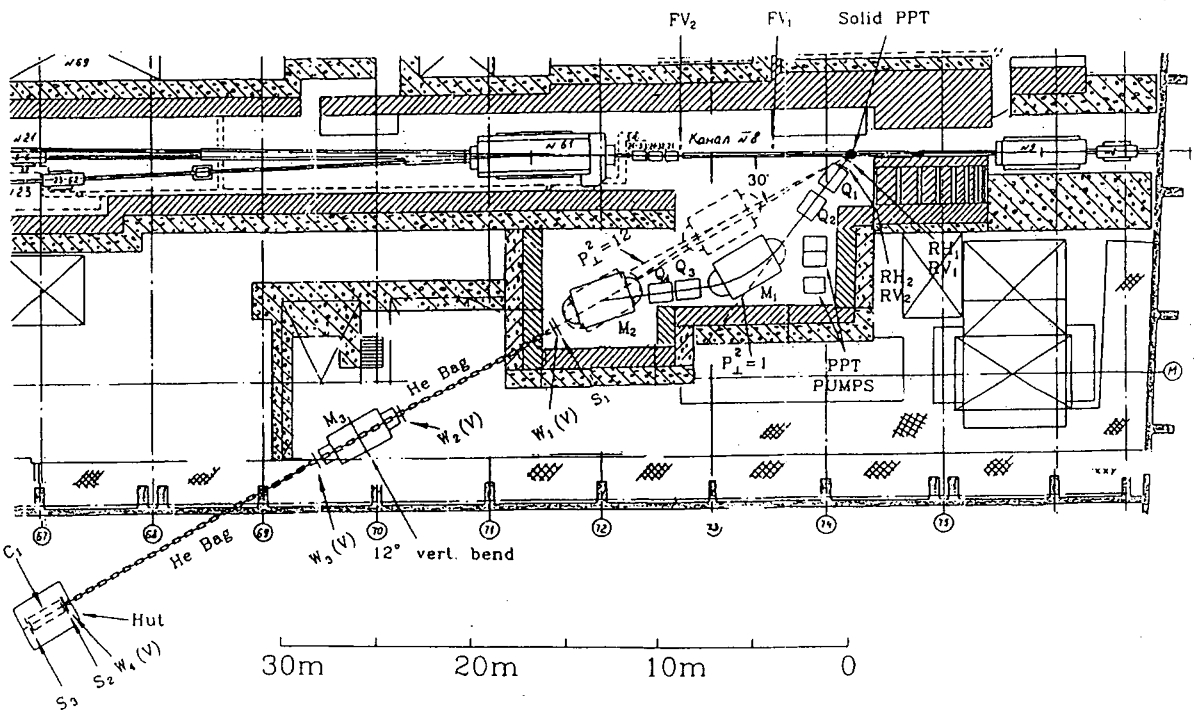

Fig. C1 SPIN@U-70 experiment at U-70 as proposed in 1996.[199]

20 November 2000

Table C1: SPIN@U-70 Collaboration

L. V. Alexeeva[a], V. A. Anferov[b], B. B. Blinov, M. A. Bychkov[c], E. D. Courant, Ya. S. Derbenev, G. Fidecaro[d], M. Fidecaro[d], S. E. Gladycheva, T. Kageya, F. Z. Khiari[e], S. V. Koutin[a], A. D. Krisch[+], A. M. T. Lin, W. Lorenzon, V. G. Luppov, V. S. Morozov[a], D. C. Peaslee[f], R. S. Raymond, D. W. Sivers[g], J. A. Stewart[h], S. M. Varzar[a], V. K. Wong, K. Yonehara

UNIVERSITY OF MICHIGAN, ANN ARBOR, U.S.A.

D. G. Crabb and students

UNIVERSITY OF VIRGINIA, CHARLOTTESVILLE, U.S.A.

Yu. M. Ado, B. V. Chujko, A. N. Davidenko, S. V. Erin, V. N. Grishin, V. A. Kachanov, Yu. V. Kharlov, V. Yu. Khodyrev, A. V. Kusnetsov, V. A. Medvedev, V. V. Mochalov, A. I. Mysnik, S. B. Nurushev, D. I. Patalakha, A. F. Prudkoglyad, V. V. Rykalin, P. A. Semenov, V. L. Solovianov, V. P. Stepanov, V. A. Teplyakov, S. M. Troshin, N. E. Tyurin, A. G. Ufimtsev, M. N. Ukhanov, A. E. Yakutin, A. V. Zherebtsov

INSTITUTE OF HIGH ENERGY PHYSICS, PROTVINO, RUSSIA

N. S. Borisov, V. V. Fimushkin, V. A. Nikitin, P. V. Nomokonov, I. A. Roufanov, Yu. K. Pilipenko

JOINT INSTITUTE FOR NUCLEAR RESEARCH, DUBNA, RUSSIA

P. P. J. Delheij, W. T. H. van Oers, A. N. Zelenski[i]

TRIUMF, VANCOUVER, CANADA

+ The spokesperson for the SPIN@U-70 Collaboration is:

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a Moscow State Univ.
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d CERN
e CAPS/RI, King Fahd Univ.
f Univ. of Maryland
g Portland Physics Inst.
h DESY-Zeuthen
i INR-Moscow

We estimate the event rates and errors in A_n for large-$P_\perp^2$ proton-proton elastic scattering at U-70 using the Michigan solid Polarized Proton Target and the proposed SPIN@U-70 recoil spectrometer in U-70's Channel 8 extracted 70 GeV proton beam-line. The Michigan PPT seems very well matched to the proton intensity available in this beam-line. Table C2 lists the estimated event rate and error in A_n at each $P_\perp^2$ point. We may run with a lower beam intensity at $P_\perp^2 = 1$ (GeV/c)^2 to reduce accidentals since the statistical precision is around 0.01%. Note that a superconducting quadrupole magnet Q_1 is required in the very-large $P_\perp^2$ region. The measurement of A_n should be rather precise, with an error of less than 1% for $P_\perp^2$ up to 6.0 (GeV/c)^2, and less than 5% up to $P_\perp^2 = 12.0$ (GeV/c)^2.

$P_\perp^2$ (GeV/c)^2	Δt (GeV/c)^2	$\Delta\phi$ mr	$d\sigma/dt$ $\frac{nb}{(GeV/c)^2}$	Events per hour	hours	Events (N)	ΔA_n $[.85\sqrt{N}]^{-1}$	
1.0	0.06	159	4000	230000	100	$2.3\ 10^8$	0.01%	
2.0	0.09	177	90	8600	100	$8.6\ 10^5$	0.1%	
3.0	0.25	194	19	5500	100	$5.5\ 10^5$	0.2%	
4.0	0.35	210	4.0	1800	100	$1.8\ 10^5$	0.3%	
5.0	0.45	225	0.9	550	100	$5.5\ 10^4$	0.5%	
6.0	0.56	240	0.22	180	200	$3.6\ 10^4$	0.6%	
7.0	0.67	254	0.055	56	200	$1.1\ 10^4$	1.1%	**Super Q_1**
8.0	0.79	268	0.016	20	300	$6.0\ 10^3$	1.5%	
9.0	0.92	282	0.0047	7.3	400	$2.9\ 10^3$	2.2%	
10.0	1.06	296	0.0017	3.2	600	$1.9\ 10^3$	2.7%	
12.0	1.25	324	0.0003	0.73	800	$5.8\ 10^2$	4.9%	
			Total hours =		3000			+ 500 (tune-up)

Table C2 Event rates and errors in A_n for $p-p$ elastic scattering at U-70.

Fig. C2 is a three-dimensional graph of the analyzing power, A_n, plotted against P_{lab} and against $P_\perp^2$. This graph summarizes most of the world's proton-proton analyzing power data from 2 to 300 GeV. At small-$P_\perp^2$, there are quite large spin effects at low energy. At high energy, these small-$P_\perp^2$ spin effects clearly decrease. The 100-150 GeV SPS data of Fidecaro *et al.* and the 200-300 GeV Fermilab data of Chamberlain *et al.* both show proton-proton elastic spin effects of only about 1% at small-$P_\perp^2$. Our high-$P_\perp^2$ AGS data, at $P_\perp^2$ of 7 (GeV/c)^2, found large spin effects at 24 and 28 GeV. The goal of SPIN@U-70 experiment is to extend these studies to the very-large $P_\perp^2$ of 12 (GeV/c)^2 and to 70 GeV, as indicated by the hand-drawn point. We hope to determine if these large spin effects, which perturbative QCD says should not exist, persist to U-70's maximum energy, and to this unexplored very-large-$P_\perp^2$ region.

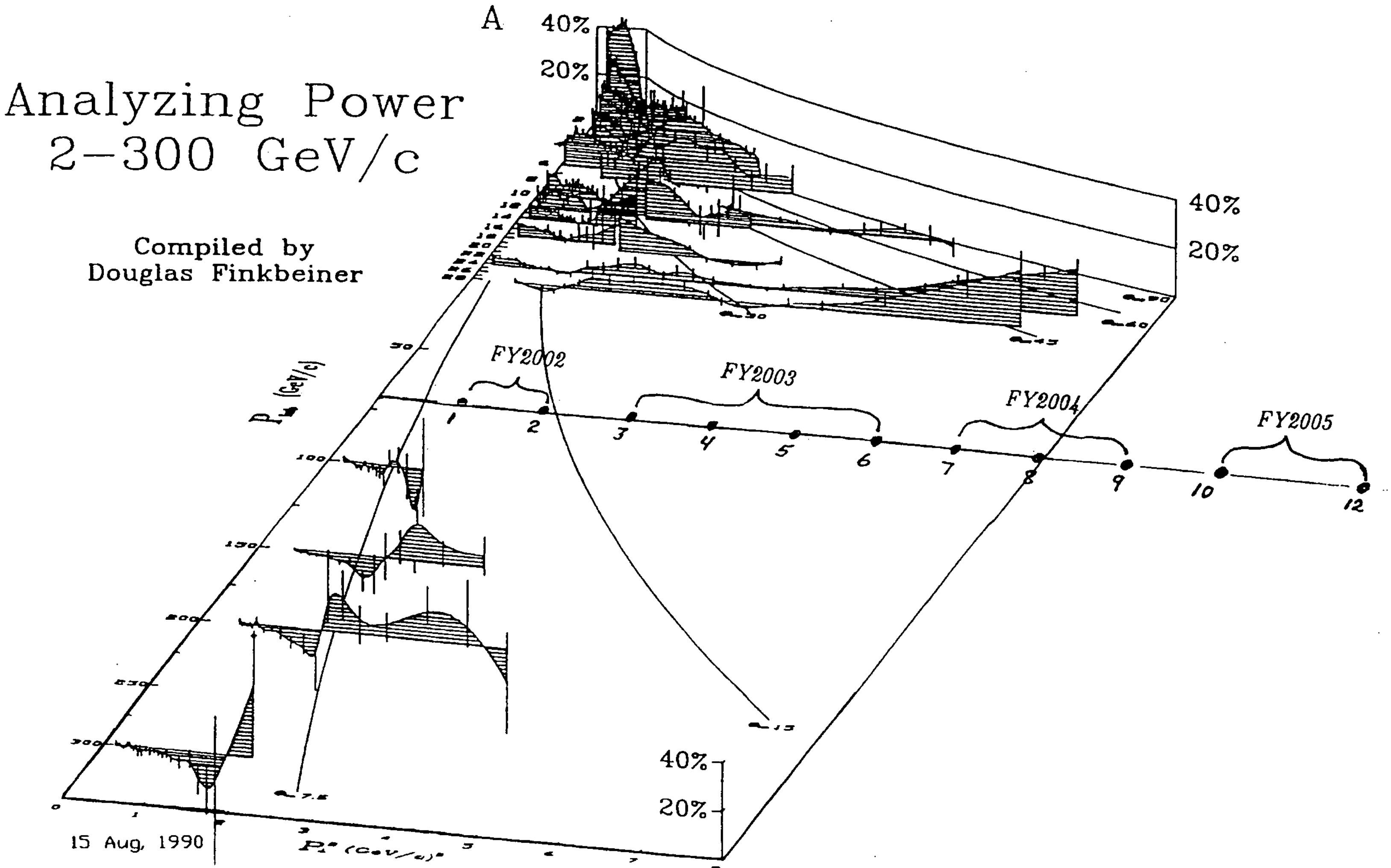

Fig. C2 Proton-proton Elastic Analyzing Power from 2 to 300 GeV/c plotted against P_{lab} and $P_{\perp}^2$.

The recoil spectrometer originally proposed in late 1996 for SPIN@U-70 (see Fig. C1) is essentially identical to the NEPTUN-A spectrometer. However, it extends outside the U-70 Building and would require the construction of a hut. To save the considerable expense of building this weather-proof detector hut at the end of the Recoil Spectrometer arm, we recently shortened the recoil spectrometer from 50 m to 32 m; thus, it would now fit within the existing building, as shown in Fig. C3. Moreover, since it would be difficult to measure the inclusive A_n with our solid NH_3 PPT, we decided not to use a Cherenkov counter.

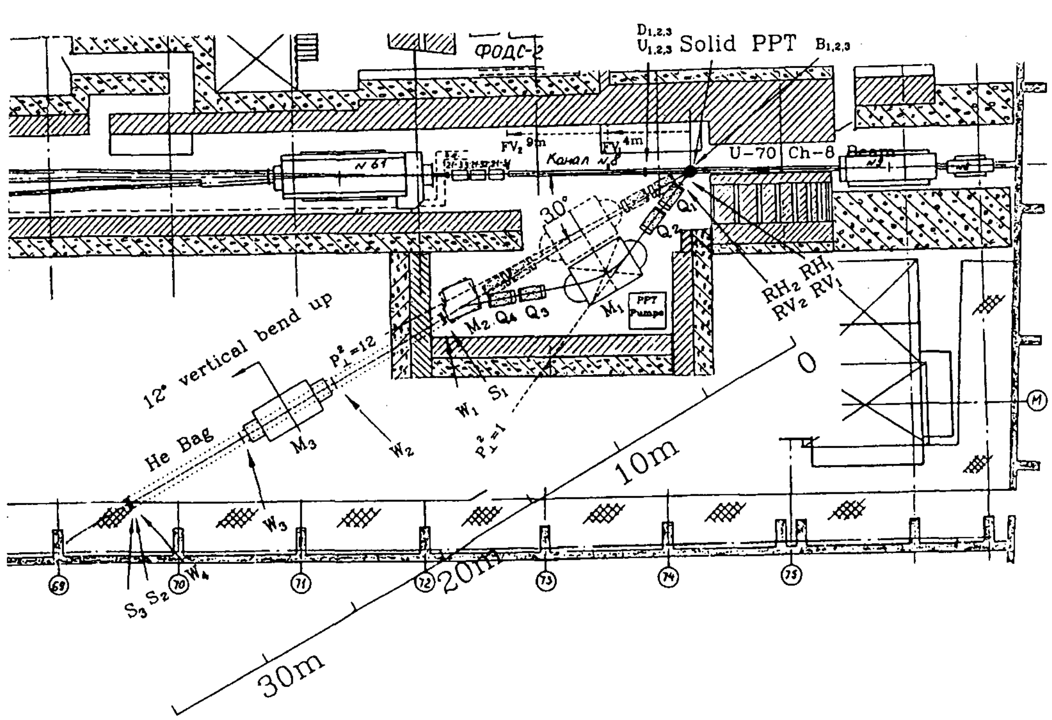

Fig. C3 SPIN@U-70 experiment with shorter 32 meter Recoil Spectrometer.

The SPIN@U-70 experiment would involve equipment installation in FY2001, two months per year of running in FY2002-2005 and data analysis and equipment return in FY2005. Below is our tentative schedule for SPIN@U-70 runs:

- The FY2002 run would probably occur either in Nov-Dec 2001 or Mar-Apr 2002. It might focus on tune-up of the Polarized Target, the Beam and the Recoil Spectrometer and some data runs at the high-rate small-$P_\perp^2$ points of: $P_\perp^2$ = 1 and 2 (GeV/c)^2.
- The FY2003 run would probably occur in Nov-Dec 2002 and would probably involve data runs at the medium-$P_\perp^2$ points of: $P_\perp^2$ = 3, 4, 5, and 6 (GeV/c)^2.
- The FY2004 run would probably occur in Nov-Dec 2003 and would probably include recoil spectrometer tune-up with the new high-gradient superconducting quadrupole at Q_1 and then data runs at the large-$P_\perp^2$ points of: 7, 8, and 9 (GeV/c)^2.
- The FY2005 run would probably occur in Nov-Dec 2004 and would focus on long runs at the low-rate, very-large-$P_\perp^2$ points of: 10 and 12 (GeV/c)^2, which may be most interesting. These would occur after the Beam, the Polarized Target and the Recoil Spectrometer were all optimized for high intensity operation. SPIN@U-70 should then be running smoothly and less Michigan people may be needed.

The status of the equipment required for SPIN@U-70 is listed in Table C3. Note that, except possibly for the short M_2 dipole, all magnets and shielding blocks are readily available at IHEP-Protvino. Significant time would be required for the careful packing, paperwork, shipping, and reassembly of the solid PPT system now at Michigan. We recently sucessfully tested this solid PPT at Michigan, with its new PC Labview software program. New more-reliable power supplies must be purchased for the PPT's 140 GHz microwave tube ($50K) and its superconducting magnet ($10K).

#	Item	Status	Suggested Action	Estimated Time
1.	Solid PPT, NMR, Microwaves	At Michigan	Pack, ship, reassemble	10 months
2.	PPT Pumps	Need	Acquire in Russia	9 months
3.	PPT Stand + hardware	At Michigan	Modify and ship	3 months
4.	Quadrupoles Q_1, Q_2, Q_3, Q_4	At Protvino	Map fields	3 months
5.	Dipoles M_1, M_3	At Protvino	Map fields	3 months
6.	Dipole M_2	From Protvino	Obtain, map fields	5 months
7.	Stands for: Q_1,Q_2,Q_3,Q_4 M_1,M_2,M_3	Need	Make at Protvino	3 months
8.	Magnets' Power Supplies	From Protvino	Obtain, check	3 months
9.	Scintillators: FV_1,FV_2,S_1,S_2,S_3 RH_1,RV_1,RH_2,RV_2	Need	Make at Michigan	4 months
10.	Wire Chambers: W_1,W_2	At Michigan	Pack, ship	2 months
	W_3,W_4	Need	Make at Michigan	6 months
11.	Detector Stands	Need	Make at Protvino or ship from Michigan	3 months
12.	Cables	Need	Purchase in Russia	2 months
	Connectors	Mostly at Michigan	Acquire, ship	3 months
	Connect cable ends	Need	Assemble, test at Protvino	2 months
13.	Electronics	Mostly at Michigan	Acquire, ship	3 months
14.	Computers	Mostly at Michigan	Acquire, ship	2 months
15.	Monitors D_{123}, U_{123}, B_{123}	At Michigan	Check, ship	3 months
16.	Profilometers	From Protvino	Check, install in beam line	2 months
17.	Feedback split SWICS	Need	Build at Protvino or Michigan	4 months
18.	Experiment's Trailer	From Protvino	Obtain, modify	3 months
19.	Shielding Blocks	At Protvino	Plan, rearrange	3 months
20.	Magnets' movement plates	Need	Design, build at Protvino	3 months
21.	Liquid Helium and Nitrogen	From Protvino	Purchase	1 month
22.	Two 500 l Helium dewars	Through Protvino	Purchase in Russia	5 months
..	......	......	......	......
23.	Superconducting Q_1	Will need later	Design, purchase or fabricate	18 months

Table C3. Status of equipment for SPIN@U-70.

C.2 Spin Manipulation of Polarized Proton and Deuteron Beams

In May 2000, we submitted to IUCF a two-part proposal.[204] This proposal focused on accelerator research which has become possible with the 1999 upgrade of the IUCF Cooler Ring involving the new Cooler Injector Synchrotron (CIS) and its CIPIOS Polarized Ion Source, which is shown in Fig. C4.

The first part was a request to extend the current experiment CE-69, *Snake Resonances and Full Snake Spin Flipping.* Since we expect to exhaust our approved 96 shifts of beam time by late 2000, we requested a 60-shift-extension of CE-69 to further increase the maximum spin-flipping efficiency using an upgraded rf-dipole both with and without a Siberian snake and to complete a detailed study of higher-order snake resonances. This extension was approved for 60 shifts with A^- priority.

The second part proposed a new experiment: *Spin Manipulation of Polarized Deuterons.* A new generation of IUCF polarized deuteron scattering experiments [CE-64, CE-78] is emerging as an interesting area of subatomic physics. As an important step towards new polarized deuteron scattering experiments, we wish to study the spin manipulation of polarized deuterons in the IUCF Cooler Ring. To manipulate the polarization of a stored deuteron beam, new equipment will be needed, including a new solenoidal Siberian snake, a stronger rf-dipole magnet, and possibly an upgraded rf-solenoid and two new electric rf-dipoles. Moreover, significant experimental research will be required to develop deuteron beam polarimetry and to manipulate the deuteron's polarization into the longitudinal direction. We requested 120 shifts of beam time to study the acceleration, storage, and spin-flipping of both vertically and longitudinally polarized deuteron beams in the IUCF Cooler Ring. This new proposal was approved for 90 shifts with A^- priority.

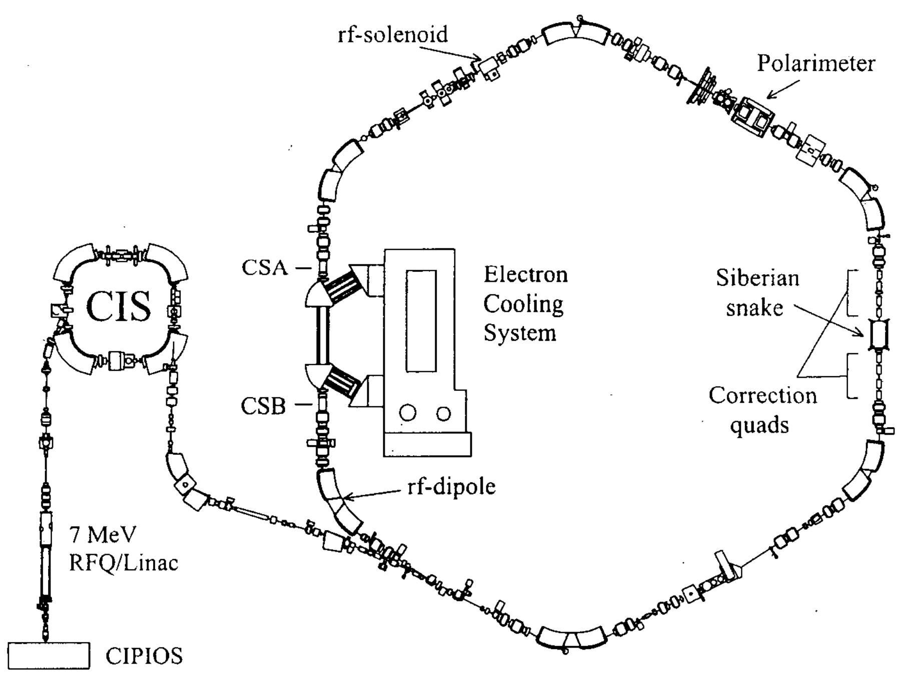

Fig. C4 Our experiments[200,204] at the IUCF Cooler Ring using the new Cooler Injector Synchrotron (CIS) and its new CIPIOS Polarized Ion Source

C.3 Michigan Ultra-Cold Spin-Polarized Proton Jet

We have now designed, fabricated and tested the 5-meter-high Michigan Ultra-cold Spin-polarized Proton Jet,[40,182,187,189] which was designed for NEPTUN-A and was shown in Fig. B25. The high power dilution refrigerator, the 12 T superconducting solenoid, the superconducting sextupole, the huge 1.2 10^7 liter s^{-1} "catcher" cryopump, and the four large cylindrical vacuum chamber modules have been fabricated and tested. The prototype rf transition unit successfully transferred e-polarization to p-polarization with a measured 95% transition efficiency[182]. Along with D. Kleppner of MIT, we tested the hydrogen maser polarimeter, which measured a test beam's polarization to a 2% precision.

The present commissioning arrangement[194] of the Jet is shown in Fig. C5. This should allow us to further improve the Jet with the goals of:

- reaching our original goal thickness of 10^{13} atoms cm^{-2},
- exceeding our current world density record of 1 10^{12} atoms cm^{-3} due to the Jet's unexpectedly good beam optics,
- install and commission the cryogenic rf transition unit to increase the Jet's proton polarization from its present 50% to near 100%.

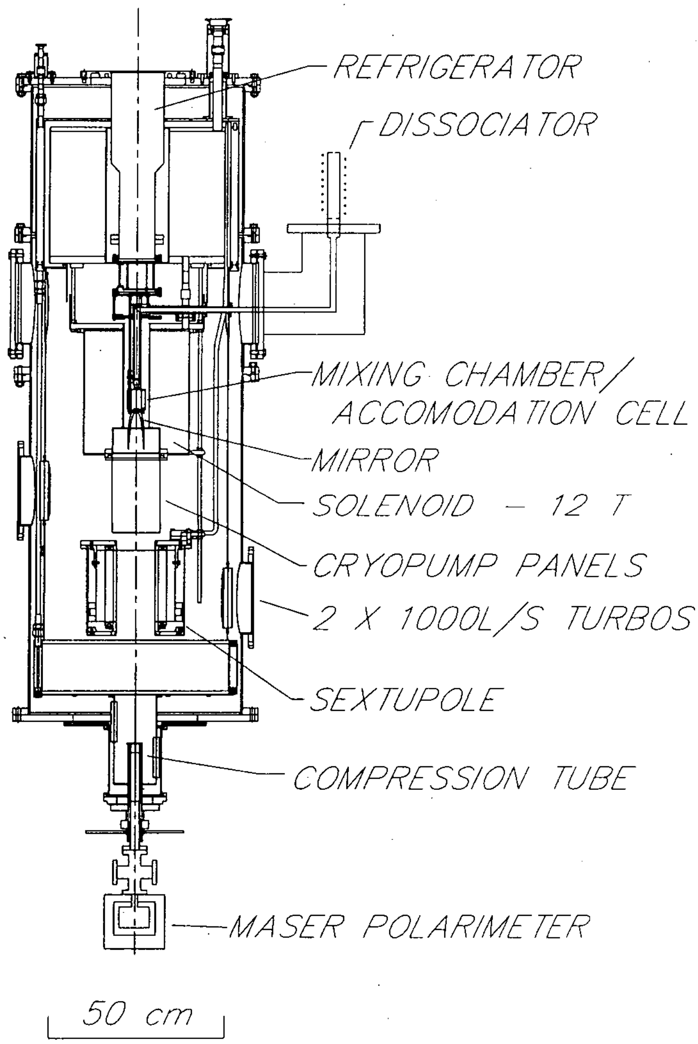

Fig. C5 Michigan Ultra-cold Spin-polarized Jet in Test Configuration.[194]

In October 1998, the Mark II Jet produced its first electron-spin-polarized atomic beam. In February 2000, tests yielded a measured cooling power of over 70 mW at 300 mK and an electron-spin-polarized atomic hydrogen beam of about 1.5 10^{15} H s^{-1} into a 0.3 cm^2 area.[187,189] The estimated proton-spin-polarization of this beam was about 50%. To obtain higher intensity and higher proton polarization, we plan:

1. to reduce the background hydrogen gas pressure using a "minicatcher" cryocondensation pump;
2. to further reduce the background ^{4}He gas pressure due to evaporation from the superfluid ^{4}He film by improving the new cryoabsorption panels;
3. to finish fabricating the 4 K rf transition unit which will convert essentially all electron-spin-polarized hydrogen atoms into proton-spin-polarized atoms.

Some recent progress[187,189,194] on the Michigan Jet is shown in Figure C6; our goal intensity corresponds to a thickness of about 10^{13} proton-spin-polarized hydrogen atoms cm^{-2}, which is about 1500 times above our October 1998 result and about 12 times above our December 2000 result.

Note that, due to the Jet's Ultra-cold 0.3 K temperature, the energy spread of the spin-polarized hydrogen atoms in the Jet's beam is only $\pm 3\%$. This has resulted in unprecedented beam optics for a neutral atomic beam which gives a measured beam size in our Compression Tube detector of diameter less than 4 mm FWHM as shown in Fig. C7. This unexpectedly small beam size has resulted in a world record density of 1 10^{12} spin-polarized hydrogen atoms cm^{-3}. This high density is especially important for experiments needing precise vertex identification such as a CNI elastic polarimeter.

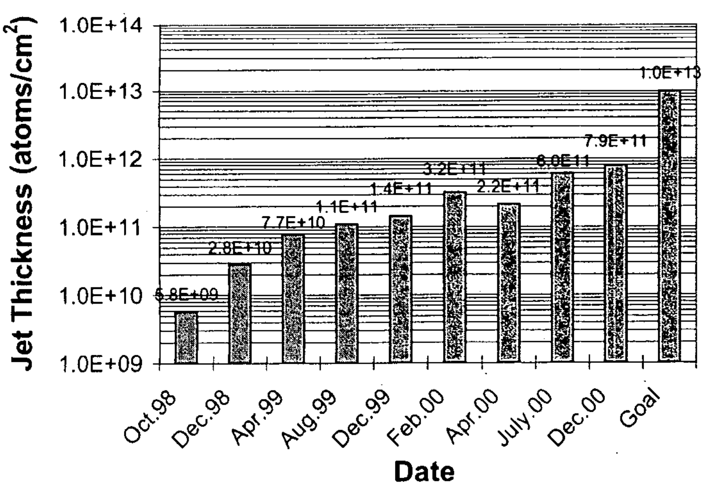

Fig. C6 Michigan Jet's Thickness vs. Run Date.[194]

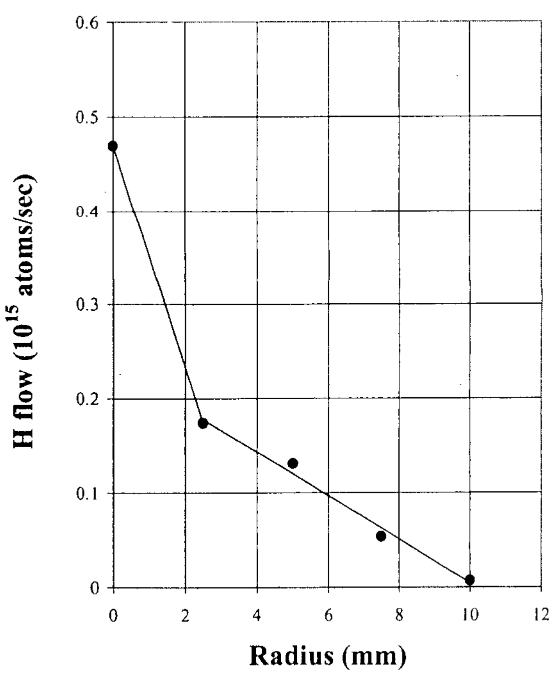

Fig. C7 Michigan Jet's Measured Radial Beam Intensity.[194]

C.4 Spin Flipper for Polarized Electron Beam at MIT-Bates

In June 1999, R. Milner, the Director of MIT-Bates, invited our Spin Physics Center to design, fabricate, install and commission, in their new 1 GeV polarized electron storage ring, a spin flipper similar to the device that we developed at the IUCF Cooler Ring. In late 1999, we agreed that MIT-Bates would provide a $150,000 two-year Grant to Michigan.

In February 2000, three physicists from Michigan participated in studies at MIT-Bates, which stored unpolarized electrons for the first time with their new Siberian snake made of 2 BINP-produced superconducting solenoids. The snake's 5 normal and skew quadrupoles were tuned with our help to compensate for the x-y coupling and focusing due to the strong solenoids. Based on our recent 86.5% spin-flipping efficiency result at IUCF,[48] we tentatively decided upon an rf-dipole for the MIT-Bates storage ring. This decision was confirmed at a late July meeting at MIT-Bates; we are now constructing this rf-dipole at Michigan using our stock of surplus ferrite from the ZGS rf-cavity.

The MIT-Bates Director also recently suggested that Michigan and the accelerator physicists in the SPIN collaboration consider joining the EPIC project to contribute to the 30 GeV polarized proton ring which would collide with a 5 GeV polarized electron ring. We were also asked to consider using our Mark-II Ultracold Jet as an internal target to study fully polarized 30 GeV p-p collisions.

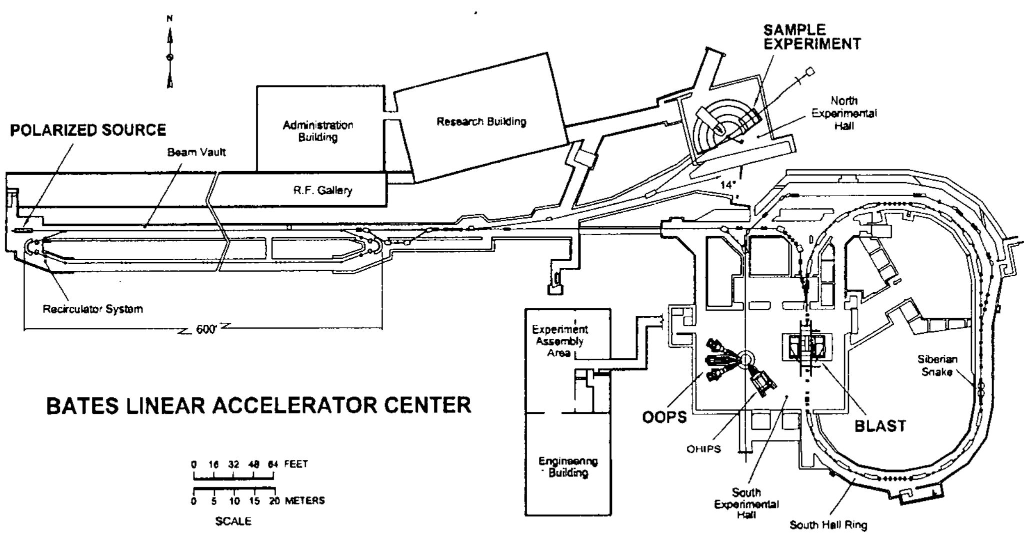

Fig. C8 MIT-Bates Linac with new 1 GeV polarized electron storage ring.

C.5 RAMPEX: Spin Effects in $p-p$ and $\pi^- -p$ Scattering at 70 GeV U-70

Partly to maintain our involvement at IHEP-Protvino, we joined our Russian collaborators in the Russian AMerican Polarization Experiment (RAMPEX) at IHEP-Protvino's 70 GeV U-70 accelerator, as discussed in Section **B.7**. A four-week RAMPEX run was part of a six-week U-70 run planned for early 1998; this run was significantly shortened due to a lack of funding for the required 50 MW of electricity, which comes from a different Ministry.

A new power distribution station PROTON is providing electric power produced by a MINATOM nuclear power station in the Kaluga region; thus MINATOM is providing its own power to IHEP-Protvino. This resolves a major issue for the experiments at both U-70 and UNK. We have sent three Michigan physicists to the RAMPEX data runs of 3 weeks in April 1999, 6 weeks in March-April 2000, and 5 weeks in November-December 2000. We plan to continue to work on the RAMPEX experiment at the recent moderate level of participation, with some possible reduction as the SPIN@U-70 effort is increased.

C.6 HERMES at DESY

Prof. W. Lorenzon, who just received tenure at Michigan, is affiliated with the Spin Physics Center. He has an NSF grant and is continuing to lead the HERMES beam polarimeter effort; moreover, he was the Deputy Spokesperson of HERMES for several years. Because of its success, HERMES will continue running for several more years.

C.7 Possible Future Experiments with Michigan Ultra-Cold Jet

In addition to the plans discussed above in Sections **C.1-C.6**, we are considering several possible polarized scattering experiments using our now-operational Michigan Ultra-cold Polarized Proton Jet as an internal target:

- NEPTUN-A: High-$P_\perp^2$ $p-p$ Elastic A_n at 400 GeV UNK;
- SPIN@HERA: Polarized Inclusive and Elastic A_n at 920 GeV HERA;
- SPIN@FERMI: Polarized Inclusive and Elastic A_n at 3 TeV Booster.

We do not have the staff to vigorously pursue any of these very interesting experiments while we are actively launching the equally interesting SPIN@U-70 experiment. We hope to focus on one of them in 2002, when it may be more clear which is practical.

C.8 Post-IUCF Siberian Snake Experiments

Around 13 November 2000, the NSF decided that the IUCF Cooler Ring will not be able to operate significantly beyond its already extended 1 October 2002 shut-down date. We have not yet had time to make a firm plan; however, we will probably try to continue our highly successful and important Siberian snake experiments at either:

- the MIT-Bates 1 GeV stored polarized electron ring, where we are now active;
- the COSY 3 GeV stored polarized proton ring, which has outstanding hardware, but is some distance from Ann Arbor.

We expect to reach a decision on this around late 2001.

D BUDGET SUMMARY (FY 1994-2001)

Year	DoE Base Operations	DoE Equipment	DoE Symposia	Fermilab	DESY*	MIT	UM Cost Sharing
FY 94	$1045 K	$250 K	–	$90 K	–	–	$75 K
FY 95	$1010 K	$ 30 K	–	$96 K	–	–	$75 K
FY 96	$ 962 K	$ 30 K	$10 K	–	$65 K	–	$75 K
FY 97	$ 902 K	$ 29 K	–	–	$58 K	–	$75 K
FY 98	$ 840 K	$ 35 K	$10 K	–	$55 K	–	$75 K
FY 99	$ 800 K	$ 40 K	–	–	–	–	$72 K
FY 00	$ 750 K	–	–	–	–	$75 K	$72 K
FY 01	$ 700 K	$ 12 K	–	–	–	$75 K	$72 K

* DM100000 per year

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3. Observation of a 96% Proton Polarization in Irradiated Ammonia, D.G. Crabb *et al.*, Phys. Rev. Lett. **64**, 2627 (1990).
4. Overcoming Intrinsic and Synchrotron Depolarizing Resonances with a Siberian Snake, J.E. Goodwin *et al.*, Phys. Rev. Lett.**64**, 2779 (1990).
5. High-$P_\perp^2$ Spin Dependent Measurements, A.D. Krisch, Z. Phys. **C 46**, S133 (1990).
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45. P. Wesolowski, Ya.S. Derbenev *et al.*, Nucl. Instrum. and Methods **A441**, 281 (2000).

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52. High Energy Spin Physics, A.D. Krisch, Invited lecture at Quarks 90 Conference, Telavi, Georgia, USSR (16 May 1990), UM HE 90-13.

53. Experiments with Siberian Snakes, A.D. Krisch, Invited lecture, Proc. of the 9^{th} International Symposium on High Energy Spin Physics, Bonn, Germany (September 10-15, 1990), eds. W. Meyer, E. Steffens, and W. Thiel, (Springer-Verlag 1991, V. 1), pp. 57-75.

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61. Analyzing Power Measurements in Elastic proton-proton Scattering at 24 and 400 GeV/c, R.A. Phelps, Invited lecture at the 4^{th} Conference on the Intersections between Particle and Nuclear Physics, Tucson, Arizona (May 23-29, 1991), AIP Conf. Proc. **243**, ed. W.T.H. van Oers, pp. 994-997.

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63. Analyzing Power Measurements in Elastic proton-proton Scattering at 24 GeV and Future Measurements at 400 GeV, R.A. Phelps, Invited talk given at the 4^{th} Spin Workshop (Protvino, USSR), 2-6 September 1991, UM HE 91-31 (August 1991).

64. Acceleration of Polarized Protons to 150 GeV at Fermilab, A.D. Krisch, Plenary lecture at SPIN-91 Workshop, Protvino, Russia (September 1991), UM HE 92-18.

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79. Polarized Proton Beams at Fermilab, R.A. Phelps, Int'l Conf. on Unified Symmetry in the Small and in the Large, Coral Gables, Florida (February 1995), pp. 293-299.

80. Status of High Energy Spin Physics, A.D. Krisch, 6^{th} International Conference on Elastic Scattering and Diffraction, Blois, France (20-24 June 1995).

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83. Polarized Proton Beams, A.D. Krisch, SPIN 95 Workshop, IHEP-Protvino, RUSSIA (18-23 September 1995), Vol. 2, pp. 254-257.

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85. Survey of High Energy Spin Physics, A.D. Krisch, Workshop on QCD, American University Paris, FRANCE (June 1996), (World Scientific), p. 46.

86. The Early Coral Gables Conferences, A.D. Krisch, 25th Coral Gables Conference, Miami, Florida (January 1997).

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98. Concluding Talk: Storage Rings, Past Present and Future, A.D. Krisch, STORI99, Indiana University (Sept. 1999).

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